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AIR POLLUTION: SYMPOSIUM ON LOW POLLUTION POWER SYSTEMS DEVELOPMENT

NATO Committee on the Challenges of Modern Society
Brussels, Belgium

1974

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The problems relating to conventional vehicle engines and measures designed to reduce emission, specifically in the light of improving fuel economy,are discussed Recent findings in the field of operational procedures for Otto and Diesel engines indicate numerous possibilities for reducing emissions and simultaneously improving the existing methods of operation. The development of new-type power systems for motor vehicles implies, however, many technological problems impedeing ~~special attention~~ their employment now and in the near future. Additionally, special attention is paid to the problems linked with the utilization of alternatives fuels for present-day motor vehicle engines. International exhaust emissions legislation, the development of new-type motor power systems as well as the development of components for conventional and new-type engines and criteria for new-type power systems are all discussed.

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COMMITTEE ON THE CHALLENGES OF MODERN SOCIETY

NATO CDSM
OTAN CCMS

AIR POLLUTION

Symposium On Low Pollution Power Systems Development

N. 39

POLLUTION ATMOSPHERIQUE

Sur Symposium Pour La Mise Au Point D' Industries à Faible Degré De

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Comite Sur Les Defis De La Societe Moderne

Preface

In our time, motor vehicle power systems cause multiple and serious problems which will certainly intensify in the future. Essential improvements and modifications of the existing power systems, therefore, belong to the priority tasks of a society dependent upon motorization, mobility and commitment to economic efficiency to meet the demands made on it. In this connection, problems pertaining to environmental protection, the economical utilization of the existing energy resources and the development of new energy sources are becoming increasingly important.

In the Federal Republic of Germany, this development is being encouraged by extensive sponsorship programs focussing on the research and development program ,,Vehicle and Traffic Technology" established by the Federal Minister of Research and Technology as well as on the ,,Traffic Emission Control Program" provided by the Federal Minister of the Interior. In these program special importance is attached to the development of low pollution power systems at reduced energy rates. Annual Status Seminars are held to report on objectives and results of the program ,,Vehicle and Traffic Technology".

Since both the CCMS Program and the Research and Development Program ,,Vehicle and Traffic Technology" are concerned with similar problems, it seemed reasonable to hold the LPPSD Symposium in conjunction with the Status Seminar.

Bonn, September 1974

Matthöfer

(Prof. Dr Maihofer)
Federal Minister
of the Interior

(Matthöfer)
Federal Minister
for Research and Technology

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Second Symposium on the Development of Low Pollution Power Systems in Connection with the Second Status Seminar Vehicle and Traffic Technology

At a special ceremonial session held to commemorate the twentieth NATO anniversary the partners of the Alliance declared their willingness to broaden the original scope of their activities by dedicating themselves to the social problems of modern society relating to the improvement of the quality of life.

In accordance with the North Atlantic Treaty of 1949, the North Atlantic Council formally established the „Committee on the Challenges of Modern Society" (CCMS) at its meeting in November 1969.

At its first plenary session, the Committee adopted, among others, a proposal for an air pollution pilot study which was presented by the US delegation. The project „Low Pollution Power Systems Development – (LPPSD)" is an integral part of this study.

Further pilot studies deal with problems concerning traffic safety, marine pollution, waste disposal and other problems of modern society.

On 14th November 1972 the United States of America, France, Great Britain, the Netherlands, Italy and the Federal Republic of Germany signed a memorandum of understanding with a view to exchanging information on the development of low pollution power systems. In order to be able to utilize the existing means with the utmost efficiency, suggestions were made to start continuous communication on new findings and on program development by the various member countries. To do so successfully the signatory states agreed to hold annual LPPSD Symposia. Sweden and Japan participate in this program.

The first Symposium was held in Ann Arbor (Mich.), USA, from 14th to 19th October 1973. The second symposium has been organized by the Federal Republic of Germany.

Under the general theme „Low Pollution Power Systems" seven topic areas will be dealing with the great variety of national and international activities. Whereas at the first Symposium in Ann Arbor the main interest was focused on the development of new type power systems, the second Symposium will give ample opportunity to discuss the problems relating to conventional vehicle engines and measures designed to reduce emission, specifically in the light of improving fuel economy. Recent findings in the field of operational procedures for Otto and Diesel engines indicate numerous possibilities for reducing emissions and simultaneously improving the existing methods of operation. The development of new type power systems for motor vehicles implies, however, many technological problems impeding their employment now and in the near future. Additionally, special attention will have to be paid to the problems linked with the utilization of alternative fuels for present-day motor vehicle engines. The Symposium will treat this problem area as a special topic.

Further subjects of discussion will be international exhaust emissions legislation, the development of new type motor vehicle power systems as well as the development of components for conventional and new type engines and criteria for new type power systems.

The Symposium is supplemented by an exhibition displaying the latest national and international technological developments on motor vehicle power systems. Both the Symposium and the exhibition will be open to the interested public.

Préface

A notre époque, les systèmes-moteur pour véhicules soulèvent un grand nombre de problèmes sérieux qui s'aggraveront encore dans l'avenir. L'amélioration et la modification sensibles des systèmes moteur est une tâche urgente si l'on veut remplir les exigences d'une société dépendant de la motorisation et de la mobilité et si l'on veut assurer le bon fonctionnement de l'économie. Dans ce contexte, les problèmes de la protection de l'environnement, de l'utilisation rationnelle des réserves d'énergie existantes et la mise en valeur de nouvelles sources d'énergie revêtent une importance particulière.

En République fédérale d'Allemagne, ce développement est encouragé dans le cadre de vastes programmes d'aide financière entrepris par le ministre fédéral de la Recherche et de la Technologie et le ministre fédéral de l'Interieur. Les priorités en sont le programme de recherche et de développement ,,Technique automobile et technique des transports routiers'', entrepris par le ministre fédéral de la Recherche et de la Technologie et le ,,Programme sur les émissions en matière de transports''engagé par le ministre fédéral de l'Intérieur. Ces programmes accordent une importance particulière au développement de systèmes-moteur peu polluants et consommant peu d'énergie. Les objectifs poursuivis et les résultats obtenus dans le cadre du programme ,,Technique automobile et technique des transports routiers'' font l'objet de séminaires-bilan organisés chaque année. En raison des problèmes analogues traités par le programme CDSM sur le développement de systèmes-moteur peu polluants et le programme de recherche et de développement ,,Technique automobile et technique des transports routiers'' il a semblé raisonnable d'organiser le séminaire-bilan de cette année dans le cadre du Symposium international LPPSD.

Bonn, septembre 1974

Matthöfer

(Prof. Dr. Maihofer) (Matthöfer)

Le ministre fédéral
de l'Intérieur

Le ministre fédéral de la
Recherche et de la Technologie

2a

Deuxième Symposium sur le développement de systèmes-moteur peu polluants en liaison avec le deuxième Séminaire-bilan sur la technique automobile et la technique des transports routiers

Lors d'une séance solennelle tenue à l'occasion du 20ème anniversaire de l'OTAN, les partenaires de l'alliance se sont mis d'accord de s'occuper, au-delà des tâches existantes, également des problèmes sociaux sous l'aspect particulier de l'amélioration de la qualité de la vie.

Lors de la réunion du Conseil de l'OTAN tenue en novembre 1969, a été institué, conformément au Traité de 1949 instituant l'OTAN, le "Comité sur les Défis de la Société moderne" (CDSM).

Lors de sa première séance plénière, le Comité a approuvé entre autres, une proposition soumise par la délégation des Etats-Unis d'Amérique de réaliser une étude directrice sur la "pollution de l'air". Un projet entrepris dans le cadre de cette étude porte sur le développement de systèmes-moteur peu polluants ("Low Pollution Power Systems Development – LPPSD").

D'autres études directrices s'occupent de questions de la sécurité des transports, de la pollution des mers, de l'élimination de déchets et d'autres problèmes sociaux.

Le 14 novembre 1972, les Etats-Unis d'Amérique, la France, la Grande-Bretagne, les Pays-Bas, l'Italie et la République fédérale d'Allemagne ont signé une convention en vue de promouvoir une information réciproque sur le développement de systèmes-moteur peu polluants. On a suggéré en même temps un échange d'information sur les connaissances acquises et, le cas échéant, une information sur les programmes entrepris par les différents pays membres, dans le but d'une utilisation aussi efficace que possible des moyens disponibles. Afin d'assurer la réalisation de ce but, les Etats signataires étaient convenus d'organiser chaque année un symposium sur le développement de systèmes-moteur peu polluants. La Suède et le Japon participent à ce programme.

Le premier symposium a eu lieu du 14 au 19 octobre 1973 à Ann Arbor (Etats-Unis). L'organisation du deuxième Symposium a été prise en charge par la République fédérale d'Allemagne.

Sous le thème général "Développement de systèmes-moteur peu polluants pour véhicules", sept groupes de travail s'occuperont de la large gamme d'activités nationales et internationales dans ce domaine. Tandis que le premier Symposium traitait en premier lieu du développement de systèmes-moteur avancés, le deuxième Symposium accorde également une grande importance aux moteurs conventionnels pour véhicules et aux mesures susceptibles de réduire les émissions de substances nuisibles sous l'aspect particulier d'une meilleure mise en valeur du carburant. L'état d'avancement actuel semble permettre, pour les moteurs à essence et les moteurs Diesel, encore de nombreuses possibilités d'amélioration du processus de travail tout en réduisant les émissions de substances nuisibles. Le développement de systèmes-moteur avancés pour véhicules soulève encore un grand nombre de problèmes technologiques qui s'opposent à une utilisation à court ou moyen terme de ces systèmes. A l'avenir, on devra également accorder une importance particulière aux problèmes de l'utilisation de carburants nouveaux dans les actuels moteurs pour véhicules. Un groupe de travail spécial du Symposium s'occupera de ces questions.

Seront traités, en outre, la législation internationale en matière de gaz d'échappement, le développement de systèmes-moteur avancés pour véhicules, le développement de composants pour des moteurs conventionnels et avancés ainsi que des critères d'évaluation pour des systèmes-moteur avancés.

Le Symposium sera complété par une exposition d'information pour montrer l'état de développement technologique le plus récent en matière de systèmes-moteur pour véhicules sur le plan national et international. Le Symposium et l'exposition d'information sont également ouverts au public intéressé.

Geleitwort

Die Kraftfahrzeugantriebssysteme werfen in der heutigen Zeit vielfältige und schwerwiegende Probleme auf. Diese Probleme werden sich in der Zukunft noch verstärken. Entscheidende Verbesserungen und Veränderungen der Antriebssysteme sind eine dringende Aufgabe zur Erfüllung der Anforderungen der von der Motorisierung und Mobilität abhängigen Gesellschaft und zur Sicherung der volkswirtschaftlichen Leistungsfähigkeit. In diesem Zusammenhang sind Probleme des Umweltschutzes, des ökonomischen Einsatzes der vorhandenen Energiereserven und der Erschließung neuer Energiequellen von besonderer Bedeutung.

In der Bundesrepublik Deutschland wird diese Entwicklung durch umfangreiche Förderungsprogramme des Bundesministers für Forschung und Technologie und des Bundesministers des Innern unterstützt. Schwerpunke bilden das vom Bundesminister für Forschung und Technologie ins Leben gerufene Forschungs- und Entwicklungsprogramm „Kraftfahrzeug- und Straßenverkehrstechnik“ und das „Verkehrs-Emissions-Programm“ des Bundesministers des Innern. In diesen Programmen kommt der Entwicklung schadstoffarmer und energiesparender Antriebssysteme besondere Bedeutung zu. Über die Zielsetzung und Ergebnisse des Programms „Kraftfahrzeug- und Straßenverkehrstechnik“ wird alljährlich in Statusseminaren berichtet. Wegen der ähnlichen Problemstellung des CCMS-Programmes über die Entwicklung schadstoffarmer Antriebssysteme und des Forschungs- und Entwicklungsprogrammes „Kraftfahrzeug- und Straßenverkehrstechnik“ lag es nahe, das diesjährige Statusseminar in das internationale LPPSD-Symposium mit einzubeziehen.

Bonn, im September 1974

(Prof. Dr. Maihofer)
Bundesminister
des Innern

(Matthöfer)
Bundesminister für
Forschung und Technologie

Zweites Symposium über die Entwicklung schadstoffarmer Antriebssysteme in Verbindung mit dem zweiten Statusseminar „Kraftfahrzeug- und Straßenverkehrstechnik"

Auf einer feierlichen Sitzung anläßlich des 20jährigen Bestehens des NATO-Bündnisses vereinbarten die Bündnispartner über die bestehenden Aufgaben hinaus, sich auch der sozialen Probleme der modernen Gesellschaft unter dem besonderen Aspekt der Verbesserung der Lebensqualität anzunehmen.

Auf der Sitzung des NATO-Rates im November 1969 wurde in Übereinstimmung mit dem NATO-Vertrag von 1949 das „Committee on the Challenges of Modern Society" (CCMS) gegründet.

Das Komitee befürwortete in seiner ersten Plenarsitzung unter anderem einen Vorschlag der Delegation der Vereinigten Staaten von Amerika, eine Leitstudie „Luftverschmutzung" durchzuführen. Ein Projekt innerhalb dieser Studie befaßt sich mit der Entwicklung schadstoffarmer Antriebssysteme („Low Pollution Power Systems Development – LPPSD").

Weitere Leitstudien behandeln Fragen der Verkehrssicherheit, der Meeresverschmutzung, der Abfallbeseitigung und andere Probleme unserer Gesellschaft.

Am 14.11.1972 wurde von den Vereinigten Staaten von Amerika, Frankreich, Großbritannien, den Niederlanden, Italien und der Bundesrepublik Deutschland eine Vereinbarung unterzeichnet mit dem Ziel einer gegenseitigen Information über die Entwicklung schadstoffarmer Antriebssysteme. Gleichzeitig wurde ein Erfahrungsaustausch über die gewonnenen Erkenntnisse und gegebenenfalls eine Information über Programme der einzelnen Mitgliedsländer angeregt, um die verfügbaren Mittel mit größter Effizienz einsetzen zu können. Um dies zu gewährleisten, einigten sich die Unterzeichner-Staaten, alljährlich ein LPPSD-Symposium abzuhalten. Schweden und Japan beteiligen sich an diesem Programm.

Das erste Symposium fand in der Zeit vom 14. bis 19.10.1973 in Ann Arbor (Mich.), USA, statt. Die Durchführung des 2. Symposiums wurde von der Bundesrepublik Deutschland übernommen.

In dem weitgespannten Rahmen nationaler und internationaler Aktivitäten wird das Symposium „Entwicklung schadstoffarmer Antriebssysteme für Kraftfahrzeuge" in 7 Themengruppen behandelt. Während anläßlich des 1. Symposiums in Ann Arbor die Entwicklung von neuartigen Antriebssystemen im Vordergrund des Interesses stand, wird auf dem 2. Symposium auch den konventionellen Kraftfahrzeugmotoren und den Maßnahmen zur Verringerung ihrer Schadstoffemissionen unter dem [illegible] Aspekt einer verbesserten Kraftstoffausnutzung ein breiter Raum eingeräumt. Nach dem derzeitigen Entwicklungsstand zeichnen sich bei den otto- und dieselmotorischen Arbeitsverfahren noch zahlreiche Möglichkeiten einer Verbesserung des Arbeitsprozesses unter gleichzeitiger Reduzierung der Schadstoffemissionen ab. Die Entwicklung von neuartigen Antriebsystemen für den Kraftfahrzeugbereich wirft noch viele technologische Probleme auf, die einen kurz- oder mittelfristigen Einsatz erschweren. Auch den Problemen der Verwendung von alternativen Kraftstoffen in unseren heutigen Fahrzeugmotoren wird in Zukunft eine besondere Bedeutung beizumessen sein. Das Symposium behandelt diesen Problemkreis in einer eigenen Themengruppe.

Weiterhin werden die internationale Abgasgesetzgebung, die Entwicklung neuartiger Kraftfahrzeugantriebssysteme, die Komponentenentwicklung für konventionelle sowie neuartige Antriebe und Beurteilungskriterien für neuartige Antriebssysteme behandelt.

Das Symposium wird durch eine Informationsschau ergänzt, auf der der neueste technologische Entwicklungsstand der Fahrzeugantriebssysteme aus dem nationalen und internationalen Bereich gezeigt wird. Symposium und Informationsschau sind auch der interessierten Öffentlichkeit zugänglich.

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Management Committee
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Organisationskomitee
Dr.-Ing. J. Bandel,
Bundesministerium für Forschung und Technologie,
Bonn, Telefon 02221/59 32 07
Dr.-Ing. D. Hartmann,
Umweltbundesamt,
Berlin, Telefon 0 30/88 50 21
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Verband der Automobilindustrie,
Frankfurt, Telefon 06 11/74 02 01
Dr.-Ing. E. Plassmann,
Technischer Überwachungs-Verein Rheinland e.V.,
Köln, Telefon 02 21/54 20 05

Management
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Organisation
Technischer Überwachungs-Verein Rheinland e.V.,
5 Köln 1, Postfach 10 17 50
Head of organization
Responsable
Organisationsleitung Dr.-Ing. E. Plassmann,
Telefon 02 21/54 20 05
Telex 888 1569

PROGRAM

Monday, November 4, 1974

morning

	Welcoming of Participants and Opening
9.15 a.m.	Oberbürgermeister of the City of Düsseldorf
9.20 a.m.	Prof. Nimet Ozdas, Assistant Sect.-General for Scientific and Environmental Affairs, NATO
9.25 a.m.	Staatssekretär Dr. G. Hartkopf, Federal Ministry of the Interior
9.35 a.m.	Ministerialdirigent Dr. W. Finke, Federal Ministry for Research and Technology
9.45 a.m.	R. Strelow, Acting Assistant Administrator for Air and Waste Management of Environmental Protection Agency, USA

SESSION 1

Comparison of National Exhaust Gas Legislations

Chairman:	Ministerialdirigent P. Menke-Glückert, Federal Ministry of the Interior
10.00 a.m.	(1) Exhaust Emissions Legislation in the European Community[+] H.P. Stief-Tauch, European Community, Brussels
10.20 a.m.	(2) Exhaust Emissions Legislation in the USA[+] E.O. Stork, Deputy Assistant Administrator for Mobile Source Air Pollution Control, Environmental Protection Agency, Washington D.C., USA
10.40 a.m.	(3) not yet decided
11.00 a.m.	Statements by Heads of Delegations on the Exhaust Emissions Legislation
11.30 a.m.	Panel Discussion
12.00 noon	Special Announcements
0.10 p.m.	Break
0.30 p.m.	Opening and Tour of the Exhibition H. Matthöfer, Federal Minister for Research and Technology or Ministerialdirigent Dr. W. Finke, Federal Ministry for Research and Technology Presentation of Electric Buses to the City of Düsseldorf Ministerialdirigent Dr. F.J. Dreyhaupt, Ministry of Labour, Health and Social Affairs, North-Rhine-Westphalia
1.30 p.m.	Lunch Break

[+] No preprint

Monday, November 4, 1974 afternoon

SESSION 2

Reduction of Exhaust Emissions for Conventional Internal Combustion Engines Considering Fuel Economy Improvements

Chairmen:	G. Donald, Department of the Environment, London, Great Britain M. Gauvin, Ministère de l'Equipment, Arcueil, France
Co-Chairmen:	Prof. Dr.-Ing. H. May, Universität Trier-Kaiserslautern Prof. Dr.-Ing. A.W. Hussmann, Technische Universität München
3.00 p.m.	(4) A Study of Technological Improvements in Motor Vehicle Fuel Consumption D.A. Hurter, A.D. Little, Inc., Cambridge (Mass.), USA
3.30 p.m.	(5) Reduction of Air Pollution by Internal Modifications of a Spark Ignition Engine Prof. Dr.-Ing. E.W. Huber, Dr.-Ing. K.H. Prescher, Institut für Motorenbau, Prof. Huber, München
4.00 p.m.	Break
4.30 p.m.	(6) The Influence of Ionisation Processes on the Reaction Kinetics in Combustion Chambers Prof. Dr. rer. nat. H. Erhardt, Dipl.-Phys. H. Günther, Lehrstuhl für Physik, Prof. Dr.-Ing. H. May, Lehrstuhl für Kraft- und Arbeitsmaschinen, Universität Trier-Kaiserslautern, Kaiserslautern
5.00 p.m.	(7) Possibilities of Lowering NO-Emissions of Spark Ignition Engines Discussed by Kinetical Modelling of the Engine Process Prof. Dr. techn. F. Pischinger, Dr.-Ing. W. Kleinschmidt, Lehrstuhl für Angewandte Thermodynamik, Technische Hochschule Aachen
5.30 p.m. - 6.30 p.m.	Social Hour
8.00 p. m.	Evening Program (by Announcement)

Tuesday, November 5, 1974 morning

SESSION 2 (Continued)
Reduction of Exhaust Emissions for Conventional Internal Combustion Engines Considering Fuel Economy Inprovements

Chairmen:	M. Gauvin, Ministère de l'Equipement, Arcueil, France G. Donald, Department of the Environment, London, Great Britain
Co-Chairmen:	Prof. Dr.-Ing. H. May, Universität Trier-Kaiserslautern Prof. Dr. techn. F. Pischinger, Technische Hochschule Aachen
8.30 a.m.	(8) Minimization of Exhaust Emissions of SI-Engines, Interrelating Effects of Air/Fuel Ratio, Mixture Preparation, Ignition, EGR and Thermal and Catalytic Treatment of Exhaust Gas Dr. rer. nat. H. Jahnke, Dr.-Ing. R. Latsch, E. Linder, K. Neidhard, D. Scherenberg, Robert Bosch GmbH, Stuttgart
9.00 a.m.	(9) Combustion Initiation in Otto Cycle Engines D.F. Moyer, J.R. Asik, W.G. Rado, A.H. Turner, Ford Motor Comp., Dearborn (Mich.), USA
9.30 a.m.	(10) Catalytic Post-Combustion of the Exhaust Gases of Otto Cycle Engines with Controlled Admixture of Secondary Air Ing. (grad.) G. Härtel, Deutsche Vergaser GmbH & Co. KG, Neuß
10.00 a.m.	Break
10.30 a.m.	(11) The Concept of the CVCC Engine System H. Sugiura, Honda Motor Comp. Ltd., Tokyo, Japan
11.00 a.m.	(12) Results from the VW-Stratified-Charged Engines Program Dr. techn. W. Brandstetter, Dipl.-Ing. G. Decker, Dr.-Ing. H.A. Kuck, Ing. (grad.) K. Reichel, Volkswagenwerk AG, Wolfsburg
11.30 a.m.	(13) Combustion Process and Exhaust Emissions of the Porsche-Stratified-Charge-System Dr.-Ing. K. Lange, Dr. techn. D. Gruden, Fa. Dr.-Ing. h.c. F. Porsche AG, Stuttgart
12.00 noon	(14) Development of the Perkins "Squish Lip" Combustion System R. Bertodo, T.W.E. Downes, I.D. Middlemiss, F. Brear, Perkins Engines Company, Peterborough, England

Tuesday, November 5, 1974 morning

SESSION 2 (Continued)

0.30 p.m.	(15) The Mercedes-Benz LDV Diesel Engine K. Obländer, H. G. Schmidt, Daimler-Benz AG, Stuttgart
1.00 p.m.	Lunch Break

Tuesday, November 5, 1974 afternoon

SESSION 3
Advanced Automotive Power Systems

Chairman: G.M. Thur, Chief, Power Systems Branch,
Alternative Automotive Power Systems Division,
Environmental Protection Agency,
Ann Arbor (Mich.), USA

Co-Chairmen: Prof. Dr.-Ing. E. W. Huber, Universität Stuttgart
Prof. Dr. techn. F. Pischinger, Technische Hochschule Aachen

2.30 p.m.	(16) Displacement Engine with Internal Continuous Combustion Dipl.-Ing. L. Sienčnik, Dipl.-Ing. J. Keylwert, Klöckner-Humboldt-Deutz AG, Köln Dipl.-Ing. P. Hofbauer, Dipl.-Ing. B. Wiedemann, Volkswagenwerk AG, Wolfsburg
3.00 p.m.	(17) Progress in Rotary Engines[+] Dr.-Ing. A. Hartmann, Audi NSU Auto Union AG, Neckarsulm
3.30 p.m.	Break
4.00 p.m.	(18) Low Pollution Combustor Development as a Part of Volkswagens Passenger Car Gas Turbine Research Program R. Buchheim, P. Walzer, Research Division, Volkswagenwerk AG, Wolfsburg
4.30 p.m.	(19) Report of the EPA/AAPSD-Chrysler Corporation Gas Turbine Development Program T. M. Sebestyen, Environmental Protection Agency, Ann Arbor (Mich.), USA C. E. Wagner, Chrysler Corp., Detroit, USA L. D. Lewis, Garrett/AiResearch, Torrance (Calif.), USA
5.00 p.m. - 6.00 p.m.	Social Hour

[+] Preprint will be delivered subsequently

Wednesday, November 6, 1974 morning

SESSION 3 (Continued)
Advanced Automotive Power Systems

Chairman:	G. M. Thur, Chief, Power Systems Branch, Alternative Automotive Power Systems Division, Environmental Protection Agency, Ann Arbor (Mich.), USA
Co-Chairmen:	Prof. Dr.-Ing. E. W. Huber, Universität Stuttgart Prof. Dr.-Ing. G. Woschni, Technische Universität Braunschweig Prof. Dr.-Ing. E. Mühlberg, Technische Hochschule Darmstadt
9.00 a.m.	(20) Development of the Nissan Gas Turbine K. Kinoshita, Nissan Motor Comp., Ltd., Tokyo, Japan
9.30 a.m.	(21) Ceramic Materials and Components for Small Automotive Gas Turbine Engines - Technology Assessment Dr. A. E. Gorum, J. J. Burke, Dr. E. M. Lenoe, Dr. R. N. Katz, Army Materials and Mechanics Research Center, Watertown (Mass.), USA
10.00 a.m.	(22) The ARPA-Ford-All-Ceramic Turbine Development Program A. F. McLean, Ford Motor Comp., Dearborn (Mich.), USA
10.30 a.m.	(23) Rankine Cycle Power Systems with Organic Based Working Fluid for Automotive Systems P. S. Patel, M. J. Armstrong, Thermo Electron Corp., Waltham (Mass.), USA
11.00 a.m.	Break
11.30 a.m.	(24) Recent Progress in Development of the EPA Program on Low Emission Automotive Steam Engine L. C. Hoagland, Scientific Energy Systems, Watertown (Mass.), USA
12.00 noon	(25) The Potentials of the Philips Stirling Engine[+] for Pollution Reduction and Energy Conservation C. L. Spigt, R. J. Meijer, Philips, Eindhoven, Netherlands
0.30 p.m.	(26) Advanced Development on Stirling Engines at MWM Dr.-Ing. F. A. Zacharias, Entwicklungsgruppe Stirlingmotor M.A.N.-MWM, Augusburg
1.00 p.m.	Lunch Break

[+] Preprint will be delivered subsequently

Wednesday, November 6, 1974 afternoon

SESSION 3 (Continued)

Advanced Automotive Power Systems

Chairman:	G. M. Thur, Chief, Power Systems Branch, Alternative Automotive Power Systems Division, Environmental Protection Agency, Ann Arbor (Mich.), USA
Co-Chairmen:	Prof. Dr.-Ing. E. W. Huber, Universität Stuttgart Prof. Dr. techn. F. Pischinger, Technische Hochschule Aachen Prof. Dr.-Ing. E. Mühlberg, Technische Hochschule Darmstadt
2.30 p. m.	(27) Status Review of Hybrid Heat Engine/Battery and Heat Engine/Flywheel Vehicles Dr. J. Meltzer, Aerospace Corp., Los Angeles, USA
3.00 p.m.	(28) Hybrid Power Systems with Kinetic Energy Storage Dipl.-Ing. H. Schreck, Dipl.-Ing. F. Torres, Institut für Kraftfahrwesen, Technische Hochschule Aachen
3.30 p.m.	(29) The Integrated System "Electric Traction on the Road" and its Development in the Federal Republic of Germany Dr.-Ing. H.-G. Müller, Gesellschaft für elektrischen Straßenverkehr mbH, Düsseldorf
4.00 p.m.	Break
4.30 p.m.	(30) Impacts of Electric Car Use in Los Angeles W. F. Hamilton, General Research Corp. St. Barbara (Calif.), USA
5.00 p. m.	(31) Na/S-Batteries as an Energy Source for Electrical Vehicles Dr. W. Fischer, Central Research Department of Brown, Boveri & Cie AG, Heidelberg
5.30 p.m. - 6.30 p.m.	Social Hour

Thursday, November 7, 1974 morning

SESSION 4

Alternative Automotive Fuels

Chairman:	J. G. **Kuiperbak**, Director of the State Office of Road Traffic, The Hague, Netherlands
Co-Chairman:	Prof. Dr. rer. nat. H. H. **Oelert**, Technische Universität Hannover
9.00 a.m.	(32) Alternative Automotive Fuels - Status and Summary of In-Progress Research Activities G. **Hagey**, Environmental Protection Agency, Ann Arbor (Mich.), USA A. J. **Parker**, Jr., R. P. Mueller a. Ass. Inc. Baltimore, USA
9.15 a.m.	(33) Possible Alternative Fuels for Internal Combustion Engines with Regard to LPG und LNG Dr.-Ing. E. **Plassmann**, Technischer Überwachungs-Verein Rheinland e. V., Köln
9.30 a.m.	(34) Alternative Fuels - Methanol R. W. **Hurn**, Bureau of Mines, Bartlesville Energy Research Center, Bartlesville (Oklahoma), USA
10.00 a.m.	(35) Comparative Results on Methanol and Gasoline Fueled Passenger Cars Prof. Dr.-Ing. H. **Heitland**, Dr.-Ing. W. **Bernhardt**, Dr.-Ing. W. **Lee**, Volkswagenwerk AG, Wolfsburg
10.30 a.m.	Break
11.00 a.m.	(36) Automotive Engine for Methanol-Water Mixture N. **Iwai**, T. **Tsuruga**, S. **Kobayashi**, H. **Sudo**, Japan Automobile Research Institute, Ibaraki, Japan
11.30 a.m.	(37) Future Roles for Hydrogen Fuel in Surface Transportation System Applications W. J. D. **Escher**, Escher Technology Associates, St. Johns (Mich.), USA
12.00 noon	(38) The Short and Medium-Term Development and Practical Application of Hydrogen-Powered Vehicles Dr. H. **Buchner**, Dr. H. **Säufferer**, Daimler-Benz AG, Stuttgart
0.30 p.m.	Lunch Break

Thursday, November 7, 1974 afternoon

SESSION 5
Component Development

Chairman:	Dr. O. Ljungstrom, Swedish Board on Technical Development, Sweden
Co-Chairman:	Prof. Dr. techn. F. Pischinger, Technische Hochschule Aachen
2.30 p.m.	(39) Ford Vehicular Gas Turbine Ceramic Regenerator Durability Development Program G. Peitsch, A. F. McLean, Ford Motor Comp. Dearborn (Mich.), USA
3.00 p.m.	(40) Compact Gas Generator for the Economic Operation of Internal Combustion Engines with Low Pollutant Emission Dr. W. Frie, Dr. H. J. Henkel, Dipl.-Ing. H. Kostka, Dr. W. Küsebauch, Dr. A. Michel, Dr. B. Paul, Dr. E. v. Szabò, Siemens AG Forschungslaboratorien, Erlangen
3.30 p.m.	(41) Investigations into the Use of the Comprex ^{R} Supercharger System on a High-Speed Diesel Car Engine Prof. Dr. E. Eisele, Dipl.-Ing. H. Hiereth, Dipl.-Ing. H. Poiz, Daimler-Benz AG, Stuttgart
4.00 p.m.	Break

SESSION 6
Assessment Criteria of Advanced Automotive Power Systems

Chairman:	J. J. Brogan, Director, Alternative Automotive Power Systems Division, Environmental Protection Agency, Ann Arbor (Mich.), USA
Co-Chairman:	Regierungsdirektor Dr. D. Frenzel, Federal Ministry for Research and Technology
4.30 p.m.	(42) Alternative Prime Movers for Future Automobiles Dr. B. Sternlicht, Mechanical Technology Inc., Latham (New York), USA
5.00 p.m.	(43) Systems Analysis of Drive Units Dipl.-Ing. P. Hofbauer, Dipl.-Ing. B. Wiedemann, Volkswagenwerk AG, Wolfsburg Dipl.-Ing. L. Sienčnik, Ing. (grad.) W. Fausten, Dr.rer.nat. U. Schmidt, Klöckner-Humboldt-Deutz AG, Köln
5.30 p.m. - 6.30 p.m.	Social Hour

Friday, November 8, 1974 morning

SESSION 7
LPPSD-Programs of the Signatory States of the Memorandum

Chairmen: Regierungsdirektor Dr. D. Frenzel, Federal Ministry for Research and Technology
Ministerialrat H. L. Dreissigacker, Federal Ministry of the Interior

9.30 a.m. Reports of the Delegations on the National Sponsorship Programs (Present Situations, Objectives, Budget)

11.00 a.m. Final Remarks on the Symposium
Ministerialrat H. L. Dreissigacker, Federal Ministry of the Interior
Regierungsdirektor Dr. D. Frenzel, Federal Ministry for Research and Technology

2.00 p.m. Conference of Government Representatives on the CCMS-LPPSD-Project
Chairman: T. Harris, Environmental Protection Agency, USA

Summary Report

Second Symposium on Low Pollution Power Systems Development

Air Pollution Pilot Study
Committee on the Challenges to Modern Society
NATO

The Second Symposium on Low Pollution Power Systems Development of the Air Pollution Pilot Study, CCMS/NATO, was held in Düsseldorf, Federal Republic of Germany, November 3-8, 1974, in connection with the Second Annual Status Seminar on Vehicle and Traffic Technology, sponsored by the Ministry of Research and Technology, Federal Republic of Germany. This Second Symposium was held pursuant to a Memorandum of Understanding entered into on November 14, 1972, between the United States of America, the United Kingdom, the Netherlands, Italy, France, and the Federal Republic of Germany, wherein it was agreed to hold annual symposia to effect continuous communication on new findings and program development on low pollution power systems for motor vehicles. To enlarge the scope of activities underway in this area, representatives of Canada, Japan, and Sweden also participate in the program.

The First Symposium on Low Pollution Power Systems Development was held in Ann Arbor, Michigan, U.S.A., on October 14-19, 1973. Whereas the first symposium focused principally on new types of power systems, the subject matter for the second symposium was expanded to include in greater detail than at the first symposium problems relating to conventional vehicle engines and measures to reduce emissions of noxious pollutants, specifically in the light of improved fuel economy.

Seven topics under the general theme "Low Pollution Power Systems" were included in the discussions at the second symposium in the following order: (1) International Exhaust Emissions Legislation; (2) Reduction of Exhaust Emissions for Conventional Internal Combustion Engines Considering Fuel Economy Improvements; (3) Advanced Automotive Power Systems; (4) Alternative Automotive Fuels; (5) Component Development; (6) Assessment Criteria of Advanced Automotive Power Systems; and (7) Low Pollution Power Systems Development Programs of the Signatory States of the Memorandum of Understanding. Brief opening and closing sessions were also included.

Over 500 people attended the meeting. Delegations representing Canada, the Federal Republic of Germany, France, the United Kingdom, Italy, Japan, the Netherlands, Sweden, and the United States of America were present. About 450 of the attendees were from European countries, and the balance from Canada, Japan, and the United States of America.

This report of the meeting will briefly summarize the major conclusions of the reports presented at the meeting, particularly with regard to the technical problems and economic impact of the various areas discussed, including the discussion from the floor following the formal reports.

Opening Session. The opening session commenced at 9:15 a.m., November 4, 1974, with introductions of the official delegations; greetings from the Oberburgermeister of the City of Dusseldorf; comments by Professor N. Ozdas, Assistant Secretary General for Scientific and Environmental Affairs, NATO, concerning NATO's science program and the role that CCMS pilot projects play in the solution of environmental problems, particularly the relationship between the Low Pollution Power Systems Development project and the automobile of the future; remarks by Dr. G. Hartkopf of the Ministry of the Interior, FRG, concerning the salutory effects of exchange of information at the symposium on standardization, energy conservation, and economic problems associated with new engine introduction; a statement by Dr. W. Finke of the Ministry for Research and Technology, FRG, relating the present symposium to the historical role of Germany in the development of motor vehicles; and remarks by Mr. R. Strelow, Assistant Administrator of the Environmental Protection Agency, U.S.A., pointing out that the technical exchange through the LPPSD project on problems of air pollution from vehicles and energy conservation will assist all Nations in protecting the public health and assuring economic stability.

Session on International Exhaust Emission Legislation (2½ hours). Immediately following the opening session, presentations were made on exhaust emissions legislation, particularly with reference to standards, by a representative of the European Community, Brussels, and by delegations from countries participating in the Symposium: the United States of America, Canada, the Federal Republic of Germany, Italy, the United Kingdom, the Netherlands, Sweden, and France. In summary, standards relating to emissions, test cycles, fuels, and noise were reviewed historically in relation to environmental and socio-economic factors pertinent to each country.

The panel discussion following these presentations pertained principally to a comparison between requirements of various countries, particularly with respect to those in the U.S.A.; the adverse role of energy conservation with respect to meeting these standards, particularly the effect of the stringent time limitations for meeting standards in the U.S.A. on fuel economy through forcing the use of modified ICE engines rather than the development of new power sources. Although not discussed as a separate topic, the important role of political factors was mentioned.

Although this session could not, of course, resolve the many problems inherent with a multitude of standards internationally, the presentations and discussions provided valuable background data against which the following technical discussions could be related.

Sessions on Reduction of Exhaust Emissions for Conventional Internal Combustion Engines Considering Fuel Economy (6½ hours). Twelve papers were presented during these sessions. Various topics were discussed relating to exhaust emissions reduction through both engine modifications and exhaust treatment, fuel economy improvements through engine modifications, and the use of advanced analytic techniques to improve technical understanding of combustion processes.

Investigators examined, utilizing computer simulation, potential improvements in fuel consumption based on near-term innovative designs of the chassis, body, engine, and transmission of a vehicle to lower its drag and rolling resistance, and improve the efficiency of the engine-drive systems. Opportunities for significant potential improvements were noted. Another computer simulation of nitrogen oxides produced during the combustion process, verified to a degree by comparison with measured emissions on an engine, investigated possibilities for NO control through modification of engine operating conditions, exhaust gas recirculation and charge stratification. The utilization of such modeling in selecting promising modifications for NO reduction was discussed.

Another paper concerned with NO control discussed the theoretical estimates of reduction initiated by increasing the ionization in the fuel-air mixture by an electrical discharge. Experiments have been initiated to test the hypothesis; however, no results have as yet been obtained.

A number of presentations dealt with the subject of affect of various combustion parameters on emissions, such as fuel preparation, ignition parameters, spark plug parameters, compression ratio, valve timing, time of injection for fuel injectors, and combustion chamber design. Reductions possible and conflicting affects on emissions control and fuel economy were cited. The possibility of highly efficient combustion of very lean mixtures through the use of wider electrode gaps, higher spark energy, and improved spark wave forms, resulting in reductions in all major pollutants (CO, HC, and NO_x), was reported and initial results of experimental tests were cited. Results of a study utilizing a single bed catalyst for simultaneous control of HC, CO, and NO_x by precise regulation of oxygen through feed-back control were presented.

Considerable interest was expressed in the results of tests on various designs of stratified charge and modified diesel engines. The combustion process and performance characteristics of the Honda CVCC

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engine system were presented, indicating that U.S. 1975 standards are met. A paper on the VW stratified charged engine indicated it to be in an advanced state of development with low NO and CO emissions and with no impairment in fuel economy and driveability. Additional development is proceeding. Results were reported on Porsche's stratified charge SKS engine; emission results were reported for conventional fuels and, in addition, for methanol and methanol-gasoline mixtures. A progress report on the Perkins "Squish Lip" combustion system for small naturally aspirated direct injection diesels was made. New designs promising capability of meeting projected future emissions standards without performance deterioration and reduced noise level were indicated. The Mercedes-Benz LDV diesel for passenger cars, utilizing a prechamber design, indicates high economy, low emissions, excellent driveability, and smoothness. Further improvements, such as supercharging, are being investigated.

Summary. Audience participation in the discussion periods following each presentation indicated a high level of technical interest in the approaches discussed, and that considerable activity paralleling that presented during the symposium is underway in the European Community as well as in the United States. The results presented since the first symposium a year ago did not indicate that any significant breakthrough had occurred; rather, and as expected, additional findings were being added to the already voluminous research results produced over the past fifteen years or so.

Sessions on Advanced Automotive Power Systems (9 hours). Sixteen papers were reported in these sessions concerning a number of power systems and related technology: internal continuous combustion engine, rotary engine, gas turbine engine, Stirling cycle engine, hybrid engines (heat engine-battery and heat engine-flywheel), electric vehicles, and advanced battery development.

Progress was reported on the development of an internal continuous combustion engine (with a reciprocating or rotating expander) that shows promise in the low power range for increased efficiency and low emissions and noise. Test results are expected early in 1975.

A report on a rotary engine developed by Audi NSU indicates that progress has been made in improving the fuel economy so that now it is comparable to the reciprocating engine. Prototype engine tests indicate capability for meeting the 1977 U.S.A. emission standards. Development continues in a number of areas including improvement of production cost and the use of stratified charge.

In the gas turbine area, progress was reported on the government (FRG) sponsored work at VW to develop two low pollutant and multi-fuel combustion systems. Emphasis has been given to the non-steady-state operating range; a number of burners have been tested using both lean and rich mixtures. Computer simulation is being used to assist in these developments.

A report on the U.S. Government sponsored EPA-Chrysler gas turbine program indicated that, whereas in the past emphasis has been placed on improved combustor technology, future activities are focused on an engine upgraded with respect to fuel economy while still attaining satisfactory emission levels. Gains can be expected by increasing cycle temperature and improvements in aerodynamic efficiency, regenerator efficiency, power augmentation, reduced heat losses, and reduced engine weight. Two interchangable combustor concepts have been selected for the upgraded engine to allow latitude in final selection with respect to future emission standards. A program is underway to develop a control system that will protect the engine through all the phases of operation and still be within the capabilities of an ordinary driver.

Considerable interest in the EPA-Chrysler program was expressed, particularly with respect to production costs and fuel economy. It was related that the future competitive status of the turbine depends on the successful development of technology that would allow increased operating temperatures at reduced production costs (e.g., ceramics) and the comparable costs of an ICE powered car with the same emission and fuel economy characteristics.

Results of investigations to improve the Nissan heavy duty gas turbine were reported. Discussion related principally to solution of mechanical problems and improvements in aerodynamic efficiency and fuel control systems. Tests were reported using a variety of fuels: kerosene, methanol, kerosene-water emulsions, and kerosene-water-methanol mixtures.

Two papers from the U.S.A. on ceramic technology development, an area of technology that bodes well for a solution to problems concerned with increased operating temperatures with improved fuel economy and reduced production costs for gas turbines, were received with a good deal of interest. One paper dealt with research and development efforts required to make the shift from 200-hour technology demonstration to 3000-hour engine life and/or component reliability demonstration. A review was presented on major unsolved problems, service goals, status of component development, status of materials and industrial capability, and major gaps in technology. A companion paper indicated developments in similar areas pertaining to materials, fabrication processes and designs to apply ceramics to vehicular, high temperature gas turbines.

The interest in ceramic technology expressed by the participants lead to the suggestion that this area should be considered by the CCMS/LPPSD project for multilateral cooperation.

Developments in Rankine cycle powered vehicles in the U.S.A. were reported. System tests of an organic fluid reciprocal expander engine indicate improvement in fuel economy to 17 mpg based on steady-state speeds and the ability to meet 1977 U.S.A. standards based on computer calculation of emissions over the Federal driving cycle using steady-state emission data as input. Progress in development of an Organic Rankine cycle power plant applied as a bottoming cycle for heavy duty diesel powered trucks was also reported. Tests indicate 15 percent improvement in fuel economy over the original diesel truck values. The concept may also be applied to supercharged engines. Developments in a water-based Rankine cycle engine with a 4-cylinder uniflow expander indicates the capability to meet the 1978 U.S. standards, but fuel economy (calculated 8 to 11 mpg) and engine weight as compared to the conventional ICE are still problems.

Reports on Stirling engine developments by Philips (The Netherlands) reviewed the potential of this cycle for low emissions, multi-fuel capability, reliability, and low noise level. Advanced designs and applications to passenger vehicles and buses were described. A zero pollution vehicle using thermal storage indicates the capability of attaining a 130 to 300 kilometer range depending on the average road speed. MWM's investigations for truck application indicate good promise for low emissions, low noise, high efficiency, multi-fuel capabilities, and good torque characteristics. Problems of size, weight, costs, and control of power output still remain; development work continues with an optimistic outlook.

A status review was presented on the hybrid heat engine-battery and hybrid heat engine-flywheel program sponsored by the EPA (U.S.A.). Analytical and test results were presented for systems, sub-systems, and components. Advances in energy systems, both batteries and flywheels, were reported. It was reported that the suspension of the program by EPA was not because of its technical feasibility, but rather because of estimated costs of the complex system required to match the performance of conventional vehicles. A program for development of hybrid power systems with kinetic energy storage (batteries or flywheel) underway in Germany was also reported; significant problems remain to be solved.

Two reports on the possible impact of electric powered vehicles for urban transportation were presented, one using Germany as the locale and the other Los Angeles (U.S.A.). In the first, the need to consider sources of transportation energy other than petroleum was reviewed in the light of reduced world petroleum resources. In this regard, the electric car was assumed to be a prime candidate as an alternative vehicle and, based on this thesis, problems in battery development, electricity distribution, and traffic were reviewed. In the Los Angeles study, environment, energy, and socio-economic impacts of electric car use were investigated for the 1980-2000 period. The use of cars using projected improved batteries permitting daily driving ranges adequate for either limited use as a second car, or for general urban use indicated only minor impact on the air environment because conventional power systems by this period are expected to have already attained significant emissions reduction. The battery powered cars would be more expensive than their conventionally powered counterparts until presently anticipated future battery depreciation costs are substantially reduced. Total energy savings with use of the electric system would be modest; however, petroleum consumption for transportation may be significant with use of electric systems through transfer of the energy source either to nuclear energy or other non-petroleum based electric utility fuels.

A report on a study based on results of sodium-sulfur battery development projected to vehicle use, including cost analyses, indicated that such batteries have the potential for meeting technical and economic requirements. Further development is needed, however, particularly in the area of power density.

Summary. Similar to developments in controlling emissions from conventional ICE engines over the past year, reports on advanced power systems indicates only a steady garnering of knowledge rather than a significant breakthrough in any one area. Production costs and fuel economy appear in general to remain as major problems with regard to making most advanced power systems, particularly those involving external combustion systems (Rankine, Stirling), competitive with internal combustion engine powered vehicles. Anticipated technological improvements for the near future, however, show promise, and work will continue on advanced power systems development world-wide.

Session on Alternative Automotive Fuels (3½ hours). Seven reports were included in this session covering several topics: status report of EPA (U.S.A.) sponsored projects, LPG and LNG, methanol, and hydrogen as fuels for motor vehicles.

The report on EPA (U.S.A.) sponsored projects concerned three categories of alternative fuels depending on source: (1) gasoline and gasoline-like fuels from non-petroleum sources such as coal and shale; (2) unconventional fuels from non-petroleum sources such as coal; and (3) non-fossil fuels (hydrogen). Evaluations have been made on the bases of cost, technological status, compatibility with the vehicle, and compatibility with marketing. Conclusions are that coal and oil shale are the most promising sources for the U.S., complete replacement before 2000 seems unlikely. Methanol appears promising for the ICE, and hydrogen is not a practical alternative in the foreseeable future. Impact studies relative to these conclusions are now underway.

A report on automotive fuel resources in Germany indicates a 140 percent increase in energy use over the 1963-1972 period, 30 percent of which in 1972 was used for motor vehicles. A study of available alternatives included gasoline and diesel fuel from coal, LPG from petroleum or coal, LNG from natural gas, methanol from natural gas and coal, and hydrogen from electrolysis of water. Of these alternatives, methanol shows most promise on both short-and medium-term bases and hydrogen on a long-term basis. Gasoline and diesel oil from coal are other possibilities.

Results of a study on methanol use in the conventional ICE in the U.S.A. were reported. Although methanol is a viable option as an alternative fuel, used either straight or as a blend with gasoline, the advantages (improved combustion characteristics, improved b.t.u. economy) are coupled with significant problems (materials compatibility, blend phase stability, carburetion difficulties, and possible production of aldehyde emissions). Work will continue to more comprehensively describe physical and combustion characteristics of methanol. A report on a study in Germany generally confirmed the previous cited conclusions. In addition it was noted that methanol is compatible with present fuel storage and distribution systems, a gradual changeover is possible, and lead emissions are reduced. However, again it was shown that fuel vaporization and distribution pose problems. It was noted that water injection can be used to reduce NO_x and aldehydes, that methanol can be used in diesels and gas turbines, and that the cost structure appears equivalent to gasoline. Another report of investigations in Japan in general agreed with previous reported results. A further advantage cited was cleaner combustion chambers due to no carbon production during combustion. Additional potential problems included greater precision needed compared to gasoline in metering for fuel injected engines, and deterioration of lubricating oil.

Concerning the possibilities for future use of hydrogen energy, a report on the hydrogen-energy systems concept was outlined, comparing hydrogen to electricity as a candidate energy carrier offering improved transportability and storability. Under this concept, use for transportation would be one of many uses including electricity generation, and industrial, commercial, and domestic use. Production, delivery and safety aspects of hydrogen use for transportation were discussed. A second paper dealing with the short-term potential of hydrogen as a fuel indicated its usefulness only for special applications such as limited urban driving. Present technology utilizing hydride storage tanks makes them superior to battery powered vehicles. Combustion and emission characteristics of hydrogen fueled vehicles are very favorable. However, because of the complete lack of an infrastructure for hydrogen, it cannot be regarded as an alternative solution to gasoline powered vehicles in the near future.

Summary. On a near-term basis and considering resources available for the production of alternative fuels, methanol appears at the present time to be the leading candidate. Gasoline and diesel fuels from coal and oil shale in general appear to involve longer developmental periods. Hydrogen offers only long-term possibilities.

Session on Component Development (1½ hours). The three papers in this session described improvements in components for the gas turbine, the gasoline powered ICE, and the diesel engine.

The problems concerned with improving the reliability and durability of a regenerator for gas turbines were related. Problems cited included seals and leakage, cracking of cores, corrosion, and inadequate ceramic properties. Durability testing using cores made of improved materials are underway.

Results of tests on a combination ICE and a catalytic generator to gasify liquid fuels indicates the ability to use very lean mixtures with no loss in fuel economy together with very much improved emission characteristics. Alternatively, improved fuel economy can be attained with slightly less than maximum possible emission quality. Extensive development in the gas generator system is required, however, before a practical system will be available.

Progress on the application for passenger car use of the Comprex supercharging system, already used for truck diesel engines, was reported. Results indicate the system to be applicable to passenger car engines. Output and torque are comparable to gasoline-fueled engines. Emission levels and fuel consumption are about the same as those of the N.A. diesel engine. However, a great amount of development is needed, not only with regard to the supercharge system, but also to the basic engine itself.

Session on Assessment Criteria of Advanced Automotive Power Systems (1 hour). Two papers were presented in this session. One from the U.S.A. reviewed problems associated with research and development activities on alternative prime movers for future automobiles. The second from Germany outlined the use of a computer model to assist in decision making regarding support for competitive alternative power plants.

In the first paper automotive issues and options in the U.S.A. were discussed. Comparison of test results using a variety of alternative power systems with emission and fuel consumption requirements indicates the need for a balanced research and development program to assure eventual optimization of the system as a whole. It was concluded that the long-term viability of the spark-ignited internal combustion engine,

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when pitted against other future prime movers and long-term availability of fuel sources, is questionable.

In the second paper on the use of a computer model to assist in selecting systems for further development, the model allows input of changing time dependent functions according to new requirements for power plants. Input to the model at present is restricted to technical considerations and ecological considerations; other areas can be added as desired. Future plans call for the addition of data to the present bank to provide improved analyses and to extend the input to include other than technical and ecological considerations.

Session on LPPSD Programs of the Signatory States of the Memorandum of Understanding (1½ hours). Reports were made not only by those countries included in the signatory States of the Memorandum of Understanding (France, the United Kingdom, the Federal Republic of Germany, Italy, the Netherlands, and the United States of America), but also by Canada and Sweden. These reports pertaining to the low pollution power systems development programs in each country were quite variable in content, ranging from listings of project areas with corresponding funding, to statements of overall expenditures, general areas of activity, and the rationale for programs in the light of national interest. In some cases, future funding beyond the period 1974-75 was noted. No consistent format was discernable to allow a collation of the information reported other than in a very general manner.

These reports, together with the presentations made during the first four days of the symposium, indicated that the programs technically were proceeding along similar lines, that these programs appeared to be complementary in some cases and overlapping in others, and that the affect of the world energy problem was evident in program changes since the first symposium a year ago.

With further regard to the overall effort involved in the LPPSD project, it had been remarked on several occasions during the technical sessions of the symposium that a comprehensive assessment of the total effort in some detail would be helpful to indicate not only areas of unnecessary overlap, but also areas of unmet need. Such an analysis would be helpful in overall planning of each country's national effort and, in addition, would pinpoint more readily possible areas for more direct coordination of activities or cooperative projects on a bilateral or multilateral basis.

(NOTE: This subject was further discussed at the Conference of Governmental Representatives on the CCMS/LPPSD project following the closing session for the symposium. It was agreed, after some discussion, that an overall analysis would be made during the coming year by the U.S.A. that would compare the programs underway within the LPPSD countries with a listing of overall needs internationally. This "overlay" analysis would be prepared from information to be supplied by each country in accordance with a format that would facilitate such a comparison. Further, it was agreed that this analysis would be reported at the next meeting of the LPPSD project a year from now for the information of both governments and private individuals for the purpose of stimulating general interest in and encouraging support for the program outside the government sponsored work area and also to promote improved coordination and direct cooperation in program areas of mutual interest.)

Closing Session. At a brief closing session for the symposium, expressions of grateful thanks were made concerning the excellent organization of the symposium with respect to both program and facilities, the high quality of the technical presentations, the formating and completeness of the preprints that contributed greatly to understanding, and, above all, the superb hospitality shown to all participants. The symposium closed at approximately 11:30 a.m., November 8, 1974.

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[illegible] ([illegible])
Professor N. [illegible] ([illegible])
[illegible] ([illegible])
Ministerialdirigent Dr. [illegible] ([illegible])
R. [illegible] ([illegible])

Begrüßungs- und Eröffnungsansprache

Klaus Bungert,
Oberbürgermeister der Landeshauptstadt Düsseldorf

Herr Vorsitzender,
meine sehr verehrten Damen und Herren,

es ist mir eine besondere Freude, anläßlich der Eröffnung dieses NATO-Symposiums den Veranstaltern und Teilnehmern aus neun Nationen im Namen der Stadt herzliche Grüße des Willkommens entbieten zu dürfen.

Meine Damen und Herren,
Sie befassen sich heute und in den kommenden Tagen mit einem wichtigen Teilbereich des Themas "Umweltschutz". Dem Nichteingeweihten mag dies zunächst vielleicht verwunderlich erscheinen: Auf den ersten Blick hat das Thema dieser Tagung ja kaum etwas mit der Aufgabenstellung eines Militärbündnisses zu tun. Andererseits meine ich, daß die Bündnispartner weitsichtig handelten, als sie auf einer feierlichen Sitzung anläßlich des 20jährigen Bestehens der NATO vereinbarten, sich über die bestehenden Aufgaben hinaus auch der besonderen Probleme der modernen Gesellschaft anzunehmen.

Die Fragen des Umweltschutzes sind zu einem Problem geworden, dessen Lösung unabhängig von nationalen Grenzen den Einsatz aller Kräfte erforderlich macht. Es ist auf absehbare Zeit gewiß eine Utopie zu erwarten, die politischen Machtblöcke könnten das gegenseitige Mißtrauen überwinden und sich gemeinsam dieser großen Aufgabe annehmen. Es ist aber immerhin ein hoffnungsvolles Zeichen, daß mit der NATO zumindest eines dieser Bündnissysteme begonnen hat, sich mit diesen Fragen, die das Wohl und Wehe der gesamten Menschheit berühren, ernsthaft auseinanderzusetzen.

Gerade auch unter diesem Gesichtspunkt ist es für Düsseldorf eine besondere Ehre, gastgebende Stadt dieses Symposiums sein zu dürfen. Ihre Arbeit gilt der Entwicklung schadstoffarmer Antriebssysteme und damit dem Kampf gegen die immer bedrohlicher werdende Luftverschmutzung. Es ist sicher kein Zufall, daß sich in der Hauptstadt des am dichtesten besiedelten und industriereichsten Landes der Bundesrepublik eine Reihe von Institutionen mit eben diesem Problemkreis beschäftigt. Als wichtigste darf ich hier das Medizinische Institut für Lufthygiene und Silikoseforschung an unserer Universität, die Düsseldorfer Außenstelle des Instituts für Wasser-, Boden- und Lufthygiene des Bundesgesundheitsamtes sowie die Kommission "Reinhaltung der Luft" des in dieser Stadt beheimateten Vereins Deutscher Ingenieure nennen. Unter dem Thema "Reinhaltung der Luft" fanden in Düsseldorf 1965 und 1969 bereits zwei nationale Tagungen und im vergangenen Jahr ein vielbeachteter internationaler Kongreß statt. Damit wurde gewissermaßen eine Tradition begründet, die nun durch Ihre Veranstaltung würdig fortgesetzt wird.

Meine sehr verehrten Damen und Herren,
das Kraftfahrzeug ist unter den Luftverschmutzern zweifellos einer der Hauptsünder. Die Hauptleidtragenden sind die Bewohner der verkehrsreichen Großstadtzentren. In absehbarer Zeit dürfte das Kraftfahrzeug jedoch kaum seine Bedeutung als Verkehrsmittel verlieren. Die Forderung der Stunde ist daher eben das, was Sie sich zum Ziel gesetzt haben: die Entwicklung von umweltfreundlicheren Antriebssystemen. Daß angesichts des weltweit steigenden Energiebedarfs und der nicht unbegrenzt fließenden Energiequellen Ihr Interesse auch einer besseren Kraftstoffausnutzung gilt, ist nur natürlich. Vor allem steht hier jedoch die Gesundheit des Menschen auf dem Spiel. Ich glaube mich mit Ihnen einig, daß unter diesem Aspekt energiepolitische Erwägungen vor den Belangen des Umweltschutzes zurückzutreten haben.

Forschung und Technik haben in der Vergangenheit im Kampf gegen die gefährlichen Dunstglocken vor allem über den großstädtischen Ballungsgebieten gewiß schon einiges erreicht. Noch sind wir aber weit davon entfernt, hier schon von einem entscheidenden Erfolg sprechen zu können. Um so mehr haben wir Veranlassung, den Erörterungen dieser Tage in Düsseldorf gute und brauchbare Ergebnisse zu wünschen. Mögen von dieser Veranstaltung und von der Arbeit in Ihren Studiengruppen neue Impulse zur Vervollkommnung der technischen Verfahren und Mittel zur Reinhaltung der Luft ausgehen.

Ihnen allen wünsche ich neben einer fruchtbringenden Arbeit zugleich einen angenehmen und anregenden Aufenthalt in Düsseldorf. Unsere Stadt bietet zur Ihrer Erholung und Entspannung vielfältige Möglichkeiten. Mögen Sie Gelegenheit finden, davon auch ein wenig Gebrauch zu machen. Zuversichtlich darf ich jedenfalls hoffen, daß Sie sich bei uns in jeder Beziehung wohl fühlen werden.

Nochmals viel Erfolg und herzlichen Dank!

Welcoming of Participants and Opening
by Prof. M.N. Özdas
NATO Assistant Secretary General for Scientific and
Environmental Affairs

It is indeed a pleasure and a privilege for me to declare open the Second International Symposium on Low Pollution Power Systems Development. First of all I would like to express our gratitude to the Government of the Federal Republic of Germany for inviting us to meet in Düsseldorf and for putting at our disposal this beautiful and colourful congress hall which, I am sure, will inspire all the speakers. I had the privilege of attending the first LPPSD symposium held in Ann Arbor in October of last year and I know from experience that these symposia, carried out under the aegis of the Committee on the Challenges of Modern Society, have attracted the attention not only of academic circles and government organizations, but of the automotive industry as well.

The major challenges confronting our world today comprise the three essential elements all beginning with an 'E': Environment, Energy (and Materials) and Economy. In fact, it would be very difficult to find a technological field more appropriate than the LPPSD project, where considerations of power, energy, environment and economy interact with each other so strongly. And this is one of the reasons why we have here more than 500 scientists and engineers to discuss the very problem that lies at the heart of the vehicle of the near future.

I am also happy to have the opportunity here to explain the important rôle the Atlantic Alliance is playing in non-military fields. Functioning virtually as an international Research Council, but with very little financial and personal resources, the Alliance has been able to encourage a wide spectrum of cooperation in Science and Technology. In fact, the NATO Science Programme has for the past 16 years provided important support for scientists, principally in the form of fellowships, research grants advanced study institutes, called summer schools, and other specialized programmes. Especially the summer schools have been noteworthy in attracting top-level scientists both from NATO and non-NATO countries, including Eastern Europe.

As regards the Committee on the Challenges of Modern Society or CCMS, this Committee adopted the pilot country concept for the solution of pragmatic problems in the environmental and related fields during the last five years. Based on this working concept or principle, one NATO country assumes full responsibility for financing, organizing and operation of a pilot study. In fact, the pilot country provides the experts, calls the meetings, prepares the reports and presents the final set of recommendations to the CCMS and to the North Atlantic Council. When these recommendations are approved they become political commitments which are implemented in the member countries.

So far, CCMS has undertaken 15 pilot studies, among which are Air Pollution, Road Safety, Inland Water Pollution, Urban Transportation and three pilot studies in the field of Energy, namely Solar, Geothermal and Energy Conservation. Thus, the United States, as pilot country of the recently completed CCMS Air Pollution pilot study, was joined by others from within NATO (Federal Republic of Germany, United Kingdom, France, Italy, the Netherlands) and outside in this important work on the development of low polluting cars.

Now the strong challenge for a new technology is here. This can be seen from the programme of this conference - in addition to improving the performance of internal combustion engines, the alternatives are becoming numerous. This time, incited by the adverse effect of pollution and driven by the never-ending creative capability of the human brain, development of low polluting engines has become a full-fledged effort. I hope that this project will follow the patterns of a number of other completed CCMS activities - the fight against ocean oil spills, the development of highly sophisticated air pollution models and the early production of prototype experimental safety vehicles. We are confident that the low polluting automotive vehicles of the future will be due in no small part to your efforts. I wish you every success in your endeavour.

Welcoming of Participants and Opening

Staatssekretär Dr. G. Hartkopf
Bundesministerium des Innern

Distinguished delegates, ladies and gentlemen,

With great pleasure I welcome you as participants in the second symposium on the development of low-pollution power-systems in Düsseldorf. My welcome is particularly cordial for two reasons:

On the one hand allow me to thank you on behalf of my Government for the high honour that your symposium which is of great significance for the technical development takes place in the Federal Republic of Germany. On the other hand as son and citizen of this town I should like personally to express my special pleasure and satisfaction that you have chosen this beautiful and active congress-city Düsseldorf as location for your event.

My special "welcome" is now adressed to my previous speaker, Assistant Secretary General Professor Ozdas who was so kind to open this NATO-CCMS-Symposium personally. With great appreciation for their work to date which I have actively supported from the very beginning on the part of the German Delegation I welcome the representatives of the pilot countries as well as the members of government and experts of the leading countries in the field of motor industry.

Here I should not fail to mention that in dealing with the overall subject which will be discussed in forum in these days, participation is in no way restricted to member countries of the North Atlantic Treaty only.

This may be understood as sign of the world-wide openess and peaceful co-existence and as a signal too for other guiding pilot-studies.

I am quite certain that the meeting held in this city will be a step forward towards the development of the motor-car of tomorrow. For we do not either wish to dispense with motor-cars in future, since they have caused a freedom of movement in an unforseeable way. What we also wish, however, in future is the reasonable use of motor-cars which is compatible with our environment. You as experts from all over the world are called upon to lead the way for us into the future by developing a motor-car which is not detrimental to the environment and thus to follow the line of reason in contrast to those who - for whatever reasons - damm the motor-car.

We may be satisfied to state by presenting their results and interim reports at regular intervals the agencies participating in this international exchange of experience, industry and science, face criticism of the experts and of their emotional opponents. I believe that criticism and encouragement are likewise needed on the long and tedious way towards the solution of our problem. Moreover, mutual information, on national focal points of development as well as promotion programmes will make it possible that the means available - which are always limited - will be used effectively.

Also from another point of view we welcome the exchange of experince agreed upon in the Memorandum of Understanding, the importance of which should not be underestimated. There is - as I believe - no doubt that compatibility of the technical systems is a fundamental precondition for the essential communication and traffic between the countries of our earth. Difficulties of harmonization and disadvantages by incompatible systems in different countries in other spheres of technology are a frequent nuisance. To a very small extent participants from the USA may have made this experience in the morning when they wanted to use their electric shaver and had forgotten to provide for the necessary adaptor. It will, however, on the other hand be fare more expensive to drive a vehicle equipped with a catalytist temporarily in a country in which only leaded petrol is available. Much more difficult it might be in the distant future to use an engine burning hydrogen gas in a country where only facilities for loading the batteries of electrically operated vehicles exist.

Mesdames et Messieurs,

L'expérience nous apprend qu'il ne sera pas facile d'harmoniser des systèmes différents dont le développement est déjà très avancé ou qui sont déjà pratiqués. Selon toute apparence, les causes techniques ayant pour conséquence de tels développements différents sont surestimées, si l'on ne prend pas en considération tous les arguments, également ceux d'ordre économique. Dans ce contexte, je pense par exemple aussi aux examens différents des gaz d'échappement pour l'admission des véhicules dans le domaine de la Communauté Européenne d'une part, des Etats Unies d'autre part et du Japon encore d'une autre manière.

Les chances pour développer des systèmes compatibles ou uniformes seront certainement les plus grandes, si un échange d'information international permanent commence déjà dans un stade initial de la recherche. J'espère donc que cet échange d'information sur le développement de moteurs émettant peu de gaz nocifs nous préservera de telles difficultés.

Dans le cadre de l'échange d'information de cette année, le Gouvernement fédéral voit avec satisfaction que l'on accorde une grande importance à l'amélioration du moteur traditionnel sous le thème de "développement de systémes-moteur peu polluants".

Nous nous sommes certainement engagés dans la bonne voie: D'une part nous ne pouvons pas attendre que, dans un avenir lointain, un nouveau moteur non-polluant sera disponible, et d'autre part se dessinent, d'aprés l'état actuel du développement, encore de nombreuses possibilités d'une amélioration du processus de travail des moteurs Otto et Diesel avec une réduction simultanée des émissions de substances nocives.

Il nous est un plaisir tout particulier que l'objectif de votre symposium se trouve en parfaite harmonie avec le programme pour la protection de l'environnement de la République fédérale d'Allemagne de l'automne 1971 (mille neuf cent soixante et onze). Nous nous sommes proposés de réduire jusqu'en 1980 (mille neuf cent quatre-vingt) les émissions des substances nocives des véhicules à moteur conventionnels à un dixième des valeurs moyennes de 1969 (mille neuf cent soixante neuf).

Le travail de recherche et de développement axé sur l'objectif de 1980 (mille neuf cent quatre-vingt) s'inspire de l'idée d'éviter, dans la mesure du possible, les dispositifs de postcombustion thermique et les réacteurs catalytiques et d'empêcher une consommation plus élevée d'essence.

Meine Damen und Herren!

Die Ergebnisse neuerer Forschungen und Entwicklungen zur Verbesserung der Verbrennungsverfahren konventioneller Antriebe berechtigen zu einem vorsichtigen Optimismus, daß das gesetzte Ziel erreicht werden kann. Diese Erwartung ist für uns jedoch kein Grund, die Hände in den Schoß zu legen und zu meinen, das Auto sei damit vor unberechtigter Kritik gerettet.

Nun, da abzusehen ist, daß die Bemühungen zur Reduzierung der Schadstoff-Emissionen zu einem zufriedenstellenden Abschluß gebracht werden können, wird der Lärmbekämpfung im Straßenverkehr neue Priorität gegeben werden müssen.

Studien der OECD über den "Einfluß des Kraftfahrzeuges auf die Umwelt" vom Oktober 1972 und des Deutschen Sachverständigenrates für Umweltfragen über "Auto und Umwelt" vom September 1973 sowie die Enquete der Europäischen Gemeinschaften über "Untersuchung der Umweltbelästigung und Umweltschädigung durch Straßenverkehr in Stadtgebieten Lärm und Abgase" vom März 1974 machen deutlich, daß auf dem Sektor Lärmbekämpfung ein erheblicher Nachholbedarf besteht.

Die Begrenztheit der natürlichen Ressourcen dieser Welt veranlassen uns alle darüber hinaus, die Bemühungen zur Minderung des Kraftstoffverbrauchs zu verstärken. Die bisher vorliegenden Einrichtungen, wie zum Beispiel

- die automatische Abschaltung des Motors im Leerlauf,
- die Speicherung der Bremsenergie oder
- die Leichtbauweise des Fahrzeugs

würden das Kraftfahrzeug jedoch erheblich verteuern. Sie sollten daher aus heutiger Sicht erst dann zur Anwendung kommen, wenn für den Käufer eines Fahrzeuges die Mehrkosten durch Minderausgaben für Kraftstoff ausgeglichen werden.

Das Gebot von Schadstofffreiheit, Lärmarmut und Ressourcenschonung ist für uns, die wir hier zusammengekommen sind, Verpflichtung, schon jetzt alle Möglichkeiten der Entwicklung neuartiger Antriebssysteme zu erforschen, wie Antriebssysteme mit schadstofffreien oder schadstoffarmen Abgasen und bei einem Energieträger, der ausreichend und preiswert zur Verfügung stehen wird.

Die Lösung dieses Problems wird weder schnell noch leicht sein. Darum ist der kurze und mittelfristige Einsatz von neuartigen Antriebssystemen zur Zeit noch nicht abzusehen. Die technischen Probleme bei der Entwicklung neuer Antriebssysteme sind eben derart umfangreich, daß heute wohl noch niemand von uns voraussehen kann, welches der bisher bekannten neuartigen Antriebssysteme eine Chance für die Zukunft hat. Es darf daher nicht mit Sicherheit erwartet werden, daß der herkömmliche Hubkolbenmotor, der in fast hundertjähriger Entwicklung zur heutigen Perfektion heranreifte, in den kommenden 20 bis 30 Jahren durch einen anderen Antrieb ersetzt werden könnte. Dies sollte man zu Beginn eines solchen Symposiums klar und deutlich sagen dürfen, damit keine falschen Erwartungen geweckt werden. Selbst wenn uns heute schon ein realisierbares Konzept eines neuartigen Antriebes bekannt wäre, könnte eine allgemeine Umstellung der Kraftfahrzeuge auf diesen Antrieb aus wirtschaftlichen Gründen erst im Verlaufe von ein bis zwei Jahrzehnten durchgeführt werden. Es wäre abenteuerlich, würde man der notwendigen Entwicklung nicht genügend Zeit lassen.

Sie als Fachleute, die an der Entwicklung neuartiger Antriebssysteme arbeiten, sollten sich durch die noch bestehenden Schwierigkeiten nicht entmutigen lassen. Ganz im Gegenteil: Gerade die besondere technische Herausforderung kann Ihnen Ansporn sein, zum Nutzen aller Menschen dieser Erde uns den Weg des Individualverkehrs in die Zukunft zu weisen.

In diesem Sinne wünsche ich Ihnen Mut, Ausdauer und Erfolg bei Ihrer weiteren Arbeit und einem guten Ablauf dieser Veranstaltung.

Lassen Sie mich zum Abschluß Dank sagen denjenigen Repräsentanten und Fachleuten der Länder, die bei der Vorbereitung dieses Symposiums tatkräftig mitgeholfen haben, insbesondere dem Technischen Überwachungs-Verein Rheinland für die Ausrichtung der Veranstaltung. Last not least gilt mein persönlicher Dank den Dolmetschern, die es auch verstanden haben, das letzte Drittel meiner Rede aus schlechtem Deutsch in excellentes Englisch und Französisch zu übertragen.

Welcoming and Opening
Ministerialdirigent Dr. W. Finke
Federal Ministry for Research and Technology

Ladies and gentlemen,

On behalf of the Federal Minister for Research and Technology, I should like to welcome you most cordially to this first international exchange of experience on low pollution power systems in the Federal Republic of Germany.
My thanks are due in the first place to those responsible members of the Committee on the Challenges of Modern Society. We consider it a great honour to have been entrusted with the organization of this Symposium, which is of such importance for the future of the automobile, our chief means of transportation.
I should also like to greet the delegations from the participating countries, the chairmen and discussion leaders of the groups studying individual themes, those presenting papers during this Symposium, the experts from industry, science and administration and, last but not least, the members of the public who wish to inform themselves on the spot as to the trends evident in automobile development. My greetings are also extended to the representatives of the press, who keep the public informed of the work being carried out in this field, which is important not only from the economic point of view, but also for enriching the lives of all of us.

In particular, I wish to express my gratitude to the Rhineland Technical Safety Control Service, which assumed the task of handling for us the organizational details. We would not have been able to arrange the Symposium at such short notice had it not been for the active support given by Dr. Plaßmann and his staff.

The 2nd national Status Seminar "Automotive and Traffic Technology" by the Federal Minister for Research and Technology has been included this year in the programme of the international Symposium. One year ago, we drew up for the first time an interim balance of the national projects promoted by the Federal Minister for Research and Technology. This year, our contributions on the leading issue of power systems form an integral part of the international exchange of experience. It will not be possible to report on all our activities within the framework of the papers to be presented here. However, the supplementary information contained in the material printed in advance, together with the interim reports selected for oral presentation, do provide a comprehensive survey of the promotion measures undertaken in this sector.

We welcome this opportunity to make an early comparison on an international basis. The development of a low pollution and, at the same time, economic, power system for the automobile of the future is a challenge which must be met by joint endeavours. The manifold interlacements in the sector of industry do not permit research and development to be carried out without profiting from the findings and experience of others engaged in different sectors. On the contrary, the knowledge available must constitute the touchstone of our own activities.

The progress made in research and technological development is not, however, merely the result of constant decision-making processes. With the rapid succession of events in today's life, it is possible that the proposed solutions which appear promising now will be forgotten by tomorrow. Flexibility and adaptability are essential prerequisites for the promotion of research, too.

I have here one of the first copies of the brochure entitled "Neuen Kraftstoffen auf der Spur". The brochure has been produced at short notice at the request of the Federal Ministry for Research and Technology. In the course of six months' intensive cooperation between research in industry, at the universities and in the big science research institutions, material was compiled concerning the technological level of development attained so far and the commercial prospects for alternative sources of fuel. Starting from raw material requirements, covering production, storage and distribution up to utilization in the motor vehicle, a critical examination has been made of the two fuel alternatives which appear to be the most promising, namely, methanol and hydrogen.

Having picked out a special group of topics for discussion at this Symposium, which are of particular relevance today, I should now like to make a few basic observations.

The development of the automobile is for ever linked to the names of Otto and Langen, Diesel, Benz and Daimler. These important German inventors provided major impulses and created the foundation for changing the character of traffic and transport to a degree which they could not have anticipated at the time. In the initial phase, however, the combustion engine was not the only subject of discussion. The steam engine and electric propulsion were rival power systems. The stages of development can be seen from the gradual increase in the maximal speeds attained during the first few years of development:

1898	63.2 km/h	with an electric vehicle
1899	105.9 km/h	also with an electric vehicle
1902	120 km/h	with a steam-driven vehicle
1902	122 km/h	with a vehicle equipped with a combustion engine
1906	195 km/h	with a steam-driven vehicle
1909	202 km/h	with a vehicle equipped with a combustion engine

During the following period, the vehicle equipped with a combustion engine proved its worth. Turbine engines alone were adopted some years later, alongside combustion engines.

Journeys made at speed may not be representative of the general technical development. Nonetheless, the question is raised why those solutions favoured at the beginning were dropped later on. In this connection, I should just like to mention the outstanding advantages of the combustion engine. Compact design, high energy density of the fuel used, a relatively favourable degree of efficiency and a performance ranging from 0.1 to 32,000 kw - these are the main characteristics of the combustion engine. No other power system possesses all of these characteristics.

A glance at the programme of papers for presentation reveals that electric power systems and also steam engines are proposed as solutions to our current problems.

Have the disadvantages of these systems been sufficiently eradicated to permit them to take their places as serious rivals to the combustion engine, or are combustion engines using alternative sources of fuel the solution where the future of the automobile is concerned?

This issue, under which yet other proposals must be included, will be debated in detail during the next few days. It will also occupy us during the years to come. Definite decisions cannot yet be taken in this respect. Decision aids are to be seen in the form of systems analysis studies, with the help of which the pros and cons can be compared with one another, to a considerable extent in a objective and lucid manner. With advancing knowledge, ever more reliable assessments can be made. However, one forecast can be made today with great certainty: in the foreseeable future, the combustion engine for operation with petrol or Diesel oil will remain the power system for the motor vehicle.

It is therefore a task of primary importance that the motor vehicle in its present form be improved to such an extent that it will be possible to compromise between the measures required for environmental protection, the demands of energy policy, the interests of the national economy and safety aspects. We cannot be satisfied with the maximization of anyone individual factor.

This compromise constitutes the optimal solution, but, above and beyond this, the automobile must also be incorporated into the entire transport system. Agreed, we do not expect any revolutionary developments in the future, but at any rate a continuous shifting of roles among individual means of transportation. Other promotion programmes drawn up by the Federal Ministry for Research and Technology aim at intensifying this shifting of roles by improving the efficiency of public means of transport with the aid of new technologies.

In my opening words, I have raised a few problems and posed a number of questions. I hope that, during the next few days, we shall be able to answer some issues - at least in part - in the course of our exchange of experience.

Together, we shall meet the challenges with which we are confronted.

I wish you all a fruitfull exchange of experience during your discussions, and that the Symposium will be a success.

Remarks by the Honorable Roger Strelow
Assistant Administrator for Air and Waste Management
Environmental Protection Agency
at the Second International Symposium
on Low Pollution Power Systems Development

It is a privilege for me to be present at the 2nd International Symposium on Low Pollution Power Systems Development. On behalf of the Chairman of the US delegation to CCMS, Russell Train, I would like to acknowledge the many hours of effort that went into organizing this meeting. I would also like to thank our hosts from the Federal Republic of Germany, the Minister of the Interior, and the Minister for Research and Technology. I want to take this opportunity to greet all the LPPSD participants, the representatives of NATO nations, and representatives of other nations who are here to share developments in the LPPSD program.

Significant progress has been made since the signing of the LPPSD Memorandum of Understanding in November 1972. At the first LPPSD Symposium held in Ann Arbor, Michigan, in October 1973, the same six nations signed an Annex to the Memorandum of Understanding. It was designed to provide an efficient means of exchanging technical information on research, development, and testing of low polluting power systems among all of the paricipants in the project. This second LPPSD Symposium is indicative of the quality of the technical exchange that we expected from the project.

Over the past twenty years in the United States, there has been serious deterioration in air quality in the major urban areas because of increases in population, urbanization, economic growth, and technological change. The air pollution created by an ever increasing number of automobiles has been a major contributor to this deterioration. By 1970, carbon monoxide, hydrocarbons, and oxides of nitrogen from motor vehicles accounted for more than half of the total pollutant emissions in the US. Similar trends are emerging in the major cities of Europe, and the growth rate of the vehicle population in Europe is now twice that of the US.

More recently, the fuel shortages experienced in the last year in many nations point up still another critical dimension to be considered in planning the future activities of the LPPSD program-fuel economy. As a result, major technical challenges are confronting our society. Major programs and investments will be needed to solve our auto-related pollution and energy problems in a manner acceptable of the public and within a reasonable time. The public health and economic stability of each of the nations must be taken into account. Early solutions and technical break-throughs needed to solve these problems will be dependent upon international cooperation.

This symposium is an excellent example of what can be accomplished when nations share technology and viewpoints. Even though the immediate problems facing each nation may be different from those of its neighbors, necessitating different emphases in the various national programs, the knowledge gained from the LPPSD program will facilitate rapid solution in each nation.

The 1970 Amendments to the US Clean Air Act provide for a major Federal program for controlling automotive emissions. Considerations of public health led to the establishment of strict emission standards for all new motor vehicles marketed in the US. US manufacturers and manufacturers of cars imported into the US are conforming with the current US emission standards. The stringent statutory standards originally set for 1975 and 1976 have been delayed until 1977 and 1978 respectively, partly in order to allow mass production techniques to catch up with low emission technology advancements.

The stringency of the auto emission controls required for model year 1978 and recently adopted US goals for better fuel economy by 1980 indicate that it is prudent to explore new and different low emission power systems. Such approaches as stratified charge engines, diesels, gas turbines, steam engines, Stirling, electrics, and hybrid combinations of these power sources are promising, but need extensive research and development. This search for advances in the development of unconventional power systems with low emissions is the essence of the LPPSD program. We must increase our attention to the fuel economy aspects of these new systems. The energy crisis that promts this effort is undeniably worldwide in scope.

We will talk much in the days ahead about automotive technology. Appropriately, the first priority in efforts to solve auto-related pollution problems involves technology. But the US Congress recognized back in 1970 that in many heavily polluted areas we must reduce auto use als well as improve emission controls if we are to meet the air quality standards set to protect public health. Restrictions on auto use, coupled with better mass transit, can of course have numerous benefits besides better air quality. The national policy adopted in the US and the progressive experience of some European nations with mass transit and parking controls suggest that auto use restrictions would be a very fruitful area for cooperative study and analysis, perhaps through the CCMS mechanism. Let me conclude with this suggestion.

Again, I welcome you all to this meeting and extend my appreciation to the organizers and hosts. We look forward to the continued success of the LPPSD and related projects.

SESSION 1

Comparison
of National Exhaust Gas Legislations

1ère SESSION

Comparaison des législations nationales en matière de gaz d'échappement

THEMENGRUPPE 1

Abgasgesetzgebung im internationalen Vergleich

The European Communities' approach to control pollutant emissions from motor vehicles

H.P. STIEF-TAUCH
ENVIRONMENT AND CONSUMER PROTECTION SERVICE
COMMISSION OF THE EUROPEAN COMMUNITIES, BRUXELLES

Control of pollutant emissions from motor vehicles has been introduced by the European Communities (EC) under the double aspect of free trade and exchange of goods and under the environmental protection. EC directives provide for control and reduction of CO and HC emissions from vehicles with positive-ignition as well as with Diesel engines. Emission limits for CO and HC have been enforced in 1974. The need for a limitation of NOx is under investigation. EC directive proposals limiting lead content in petrol and sulphur content in gas-oils are still under discussion before the Council of Ministers.

Le contrôle des émissions de polluants provenant des vehicules à moteur a été introduit dans les Communautés Europeennes (CE) sous le double aspect du libre échange commercial et de la protection de l'environnement. Des directives communautaires arrêtent le contrôle et la réduction des émissions en CO et HC provenant des vehicules équipés des moteurs à allumage commandé ou des moteurs Diesel. Les limitations à l'émission du CO et des HC ont été renforcées en 1974. La nécessité d'une limitation des emissions des NOx est à l'examen. Des propositions de directives communautaires limitant la teneur en plomb dans l'essence et la teneur en soufre dans les gas-oils sont encore en discussion devant le Conseil de ministres.

1. INTRODUCTION

There is increasing worldwide concern over the quantities of noxious substances released into the atmosphere, an important fraction of which is coming from the automobile exhaust. Attention was first directed towards this form of environmental pollution during the 1940's when residents in Los Angelos, California, became aware of the phenomenon now called photochemical smog. Studies showed that smog formation resulted from reactions between nitrogen oxides and hydrocarbons in strong sunlight producing compounds which act as respiratory irritants. Although the peculiar climatic and geographic conditions of Los Angelos certainly favour the appearance of smog, the very high vehicle density in the region with its large quantities of HC and NO_x emissions constituts by no doubt a vital factor to the smog formation.

Photochemical smog is also a well-known phenomenon in the Tokyo area or in the Canberra region in Australia. Concern over pollutant emissions and especially automobile emissions is therefore international and many governments have either adopted regulations for control of noxious emissions or have legislation under review.

The principal pollution gases present in automobile exhausts are carbon monoxide (CO), unburnt hydrocarbons (HC), nitrogen oxides (NOx). All are poisonous in various ways and degrees and current legislation is directed towards progressively reducing the emission level of these gases to a minimum, given current technology and reasonable costs. Other pollutants being of concern are lead compounds coming from the combustion of gasoline where often organic lead compounds are added as an anti-knock device, smoke emitted upon uncomplete combustion of gas-oils within Diesel engines, and, to a lesser extent, sulphur dioxide from the sulphur content of gas-oils.

2. First attempts to decreasing motor vehicle emissions

These pollutants are formed and emitted in various ways, consequently different methods for their abatement must be sought:

- Unburnt hydrocarbons (HC) are mainly emitted by the crank-case venting and by evaporation of gasoline;
- CO and NOx, as well as smoke, sulphur dioxide and anorganic lead compounds are formed as reaction products of the combustion process and are emitted from the exhaust system.

A first legal step to reduce HC emissions was made as early as 1961 in California requiring a recycling of crank-case gases, first for new vehicles, from 1964 on also for used ones, then extended to the whole territory of the USA.

Such recycling allowing for a decrease of HC emissions by about 30 % over the uncontrolled state was partly introduced also in Europe around 1960 in newly constructed motors. But it was not before January 1969 that the FRG and France introduced a legal obligation to equip the engines of new motor vehicles with this device.

3. The European approach

National legal measures aiming at a decrease of pollutant emissions from automobiles are by definition limited to the territory of the state making such provisions. With a view to the increasing commercial exchange of motor vehicles and goods and to the important number of tourists crossing national boarders with their automobiles it was obviously most desirable to look for international cooperation in this field. Thus, already on 20 March 1958, in the frame of the United Nations' Economic Commission for Europe (ECE) at Geneva an Agreement was made concerning the Adoption of Uniform Conditions of Approval and Reciprocal Recognition of Approval for Motor Vehicle Equipment and Parts.

In the frame of this Agreement nearly thirty regulations aiming at a setting of common rules on technical, administrative and safety aspects of motor vehicles have been issued and ratified by numerous European signatary.

Among those regulations two are of particular interest for the emission control of pollutants:

- Regulation No. 15 "concerning the approval of vehicles equipped with a positive-ignition engine with regard to the emission of gaseous pollutants by the engine" published in 1970, and
- Regulation No. 24 "concerning the approval of vehicles equipped with Diesel engines with regard to the emission of pollutants by the engine", published in 1972.

Several European ECE Member States applied these regulations more or less quickly on their own territory, others still hesitate to ratify them.

4. The European Communities' approach

Within the European Communities (EC) the problem of decreasing pollutant emissions from motor vehicles has received a double approach: At the one hand the obligation is fixed by the Treaties to establish a free exchange of goods between Member States, on the other hand, under the terms of the programme of action on the environment, the Commission of the EC has launched a number of actions aiming at abetter protection of the population against the nuisances created by motor vehicle emissions.

4.1 The aspect of free trade and exchange of goods

One of the most important goals of the common market is the establishment of a free circulation for goods and services between the Member States. At this end customs and similar duties have been abolished within the EC, the harmonisation of the tax systems is under way. Nevertheless for an important number of goods there subsisted many national regulations and specifications which have similar effects as custom-duties, the so-called technical barriers to trade.

In order to arrive, on a Community level, at uniform rules for the commercial exchange of motor vehicles and parts, the product "motor vehicle" was included in the "General programme for the elimination of technical barriers to trade", adopted by the Council of Ministers in April 1969 und supplemented by the Resolution of 21 May, 1973.

Under this programme on 6 February, 1970 a Council directive 70/156/ EC was approved laying down the requirements for the EC type approval procedure for motor vehicles and their trailers to be applied in respect of each type of vehicle.

With a view to the harmonisation of national requirements on pollutant emissions from motor vehicles in the frame of the type approval procedure, the ECE Regulation No. 15 was taken over as such by the Member States of the EC on 20 March, 1970 as directive No. 70/220/ EC and came into force on 1 October 1971. Similarly the ECE Regulation No. 24 was taken over too as such on 2 August, 1973 as directive No. 72/306/ EC and came into force in principle on 2 February, 1974.

4.2 The aspect of environmental protection

In 1972 the Commission's services started to set up a comprehensive Community programme of action in the field of environmental protection. This programme was definitely adopted by the Council of Ministers on 22 November, 1973. In the first phase it is particularly aiming at a decrease of pollutions and nuisances. For each different category of pollution the appropriate level of action (local, regional, national, Community, international) is to be established that befits the type of pollution and the geographical zone to be protected.

As far as pollutant emissions from motor vehicles are concerned, it is obvious that only actions at Community level are able to render the desired results.

In implementing an efficient environmental protection policy special attention must be paid to those products the use of which may lead to harmful consequences for man or the environment.

Moreover, differences as between Member States in the assessment of such risks might possibly lead to the creation or the reintroduction of barriers to trade, which would be detrimental to the satisfactory operation of the common market. That is why the implementation of the general programme for the elimination of technical barriers to trade can constitute, in so far as it concerns polluting products, an effective environmental policy instrument. The directives adopted under this programme must be regularly revised in order to adapt them to scientific and technical progress.

In the case of polluting products such measures of harmonisation must be accompanied by

- special investigations into the harmfulness of the polluting agents in these products,
- investigation and research into the possibilities of changing the composition, design or properties of these products with a view to reducing their harmfulness and, if necessary, to replace them by less or non-pollutant substitutes,
- investigation into the economic consequences of the proposed measures.

In the programme of action on the environment priority is given, as far as the harmonisation of the specifications for polluting products is concerned, to motor vehicles, noisy products and equipment, automotive fuels and fuel-oils.

5. The legal provisions and their implementation

5.1 CO and HC emissions

With the adoption of the two ECE Regulations No. 15 and No. 24 as Community directives uniform requirements have been established for the type approval for new types of motor vehicles as well as for conformity of the series production within the Member States with regard to emission control of exhaust gases.

Thus directive 70/220/EC, in force from 1 October, 1971 sets limitations to the emissions of CO and HC from light duty motor vehicles equipped with a positive-ignition engine. At this end the vehicles are submitted to different types of tests defined in this directive.

Type I test verifying the average emission of pollutants in congested urban area after a cold start of the engine is based on a driving cycle specifically designed to simulating typical European traffic conditions.

The different periods of idling, acceleration, steady speed and deceleration which the vehicle undergoes during this cycle are simulated on a dynamometer bench. The cycle is run 4 times consecutively under carefully controlled test conditions, all exhaust gases are collected in large bags and subsequently analysed. The average speed during the test is 19 km/h, the equivalent distance for the whole test with it's 4 cycles is 4.05 km.

The emission limits are given in terms of the total mass of CO and HC related to the reference weight of the motor vehicle, the numerical values for the emissions are expressed in grammes of pollutant/test.

Type II test verifying the CO emission at idling speed is carried out immediately after the fourth cycle of the type-I test. The CO-content by volume of the exhaust gases emitted with the engine idling must not exceed 4.5 %.

Type III test verifying emissions of crank-case gases is carried out on all vehicles submitted for type approval except those having a two-stroke engine with compression in the crank-case.

For compliance with this test the engines must be equipped with a crank-case gas recycling assuring that the mass of HC contained in the crank-case gases not recycled by the engine must be less than 0.15 % of the mass of the fuel consumed by the engine. The HC content is measured by means of the non-dispersive infra-red analyser sensitized to n-hexane.

The same directive sets also emission limits with which the motor vehicles of the series production must comply after having received the type approval. However, the requirements for conformity are less stringent than for the type approval, the emission limits for CO and HC established for the type I test are 20 % higher than for the type approval in order to take account of fabrication tolerances.

5.2 Smoke emissions

Pollutant emissions from motor vehicles equipped with a Diesel engine are dealt with by the Community directive 72/306/EC, being in force in principle from 2 February, 1974. For reasons of the working principle of the Diesel engine (constant air flow and power control by the quantity of gas-oil injected) the CO emissions are much smaller than with the positive-ignition engine; however, partly unburnt HC are emitted together with soot forming the well-known smoke clouds of lorry exhausts.

The directive specifies two tests which the engines have to undergo for type approval. In the first one the emission of smoke is measured at 6 different steady speeds over the full-load curve by means of an opacimeter. The directive sets emission limits in the form of absorption coefficients related to the nominal air flow passing through the engine, with which the results obtained during test one must comply.

In the second test carried out immediately after the first one the engine is accelerated freely at least six times so as to obtain maximum delivery from the injection pump until maximum engine speed is reached and the governor comes into action.

The arithmetical mean of four stabilized maximum opacity values read each time during the test is used for the determination of the absorption coefficient to be affixed indelibly to the vehicle. This test is used to check conformity of series production engines with the absorption coefficient established during the type approval test. Both directives contain a specification for the reference gasoline and gas-oil respectively to be used. Both directives provide for an adaption of the technical requirements to scientific and technical progress made. The introduction of these directives resulted in a decrease of approximately 40 % of CO emissions and 30 % of HC emissions as compared to the non-regulated situation.

6. The enforcement of emission controls for motor vehicles

With a view to the technical progress and better environmental protection an adaption of the directive 70/220/EC was foreseen, at a date enabling Member States to implement the amendments before 1 October, 1974.

Thus on 28 May, 1974 the directive 74/290/EC was adopted by the Council of Ministers, providing for a further decrease of CO emissions by 20 % and for HC emissions by 15 %, to become effective at 1 October, 1975 for the type approval of all motor vehicles equipped with positive-ignition engines as well as for vehicles put into service for the first time.

Moreover, from 1 October 1976 no motor vehicle is authorized to receive EC or national type approval or to be put into service for the first time if it is not equipped with a carburetor preventing any adjustment by the user of the vehicle influencing the CO emissions at idling speed of the engine.

After the implementation of this amended directive the CO emissions of all new motor vehicles with positive-ignition engines put into service within the EC will thus be decreased by about 60 % and HC emissions by about 45 % with respect to the non-regulated situation.

The environment programme provides also for the establishment of proposals for directives on the maximum amount of lead in petrol and for the maximum sulphur content of fuel-oils.

The Commission has forwarded to the Council on 5 December, 1973 a directive proposal on the lead content in petrol which is still under discussion. This proposal stipulates a general limitation of lead content in all types of petrol at 0.4 g/l as from 1 January, 1976 on.

From 1 January, 1978 the maximum lead content of regular grade petrol is to be decreased further at 0.15 g/l, while maintaining a RON of not less than 90; the maximum lead content for premium grade remains fixed at 0.4 g/l, with a corresponding RON of not less than 98 and a MON not less than 87. With a view to the eventually increased emission of dangerous HC the directive proposal stipulates that the reduction of the lead content shall not be such as to lead to any modification in the composition of the petrol which is likely to increase significantly the quantities of other pollutants currently emitted in the exhaust gas.

In February 1974 the Commission has forwarded to the Council also a directive proposal on the decrease of the sulphur content in gas-oils.

Two types of gas-oil are envisaged; the sulphur content of type A will be limited to 0.5 % in weight as from 1 October, 1976 and to 0.3 % from 1 October, 1980; automotive gas-oil falls under this category.

At the same dates, the sulphur content of type B gas-oil will be limited to 0.8 % in weight and to 0.5 % respectively, this B-type quality can only be used in regions with low SO_2 pollution.

7. The future work in this field

Further amendments to Community directives adopted are foreseen by the environment programme as well as the implementation of national measures before 1 October, 1976 concerning air pollution by exhaust gases from positive-ignition engines, so as to take into consideration the latest scientific progress. At this end the Commission is carrying out studies on the technological possibilities of reducing nuisances due to motor vehicles.

Consideration will be given also to the economic consequences of the proposed measures. Moreover, since two years studies are being carried out to assess more precisely the harmfulness of pollutants emitted by motor vehicles. With this knowledge it will be possible, without having resort to arbitrary values, to set limits to the presence of pollutants in the environment and to determine quality values for products in terms of standards designed to protect human health and the environment.

For reasons of the poor knowledge on the effects of nitrogen oxides on man and the environment the programme of action does not provide right now a reduction of NO_x emission from motor vehicles.

This does not mean that the Commission remains inactive in this field. On the contrary, an objective evaluation of the risks especially to human health incurred by the presence of NO_x in the ambient air is one of the priority actions of the programme. This work allows to determine the relations between exposure and effects giving thus a basis for appropriate measures at Community level which might be taken against increasing levels of NO_x in the ambient air. In the meantime, pending completion of these studies, the implementation of preventive measures to reduce sources of NO_x pollution will be considered in discussion with the Member States.

In conclusion the European Communities' approach to control pollutant emissions from motor vehicles has been defined in a way to take account of the specific situations prevailing within the Member States on technical as well as on economic grounds. Careful consideration will be given to the side effects of further control measures before implementing them at Community level. Nevertheless actions which doubtlessly prove to be necessary for the protection of public health must be implemented as soon as possible despite opposing economic or other considerations.

This is the governing principle persued by the Commission in conducting work in the field of pollution control and abatement and specifically in the field interesting all of us here.

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The U.S. Position on Automotive Emission Controls

by

Eric O. Stork
Deputy Assistant Administrator
for Mobile Source Air Pollution Control
U.S. Environmental Protection Agency
Washington, D.C.

For delivery at

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The Clean Air Amendments of 1970 -- commonly known as the Muskie Law, for its chief sponsor, Senator Edmund Muskie of Maine--set in motion a vast array of requirements and action that in the aggregate will some day abate air pollution in the United States. Among these requirements was the establishment of stringent emission limitations for automobiles. Automobiles are a primary factor in the pollution of the air in our cities--the cities in which the majority of our citizens work and live.

Concern about automobiles as a major contributor, if not the major contributor, to urban air pollution is a post-World II phenomenon. The concern initially grew out of the "smog" that began to foul the crisp, clean air of Southern California as the population of that area grew and became increasingly motorized. Effective with the 1966 model year , California required new automobiles to control tailpipe emissions of unburned hydrocarbons and of carbon monoxide. The U.S. Federal Government followed suit two years later by establishing for the 1968 model year essentially similar emission control standards on a nationwide basis.

As regards oxides of nitrogen, California added control of this pollutant to its standards effective with the 1971 model year. The Federal Government followed suit and required control for oxides of nitrogen nationally for the 1973 model year. That, pretty well, is where the matter stood by the summer and fall of 1970, when the Congress was considering extension of the Air Quality Act of 1967.

The Clean Air Amendments of 1970 provided for extremely stringent emission limitations for automobiles for hydrocarbons and carbon monoxide in the 1975 model year, and for nitrogen oxides in the 1976 model year. To understand what the Congress did, and why it did it, we have to look at the rationale for taking action in emission control that preceeded this particular piece of legislation.

All of the auto emission standards that had been set prior to the Clean Air Act of 1970 had reflected judgment of degress of emission control that were reasonably achievable in terms of known technology, within a given timetable for implementation. That is not to say that everything required of the industry up to that time had been easy for the industry to do. In some cases, it was so far from easy that industry had found it necessary to drop certain models because they could not meet the emission control standards. However, on the whole there never had been any real question about whether it was possible for industry to comply with the emission standards up through the 1973 NOx standard. The only question that might arise was how much it would cost to meet those standards in terms of reduced vehicle performance and reduced vehicle fuel mileage.

While such a policy for setting emission standards was being pursued, there was also underway a search to define the degree of emission control that would ultimately need to be achieved so that air quality standards in our major urban centers could be met. Thus auto emission standards in the Clean Air Amendments of 1970 reflected the best available estimates of how much control would be needed to achieve this goal even though the emission control technology needed to achieve these emission standards had not--at the time of the law's passage--been demonstrated to be available.

The Clean Air Act of 1970 way of setting emission standards, therefore, was a major departure from the way in which such standards had been set in the past; up through the 1973 standards, while the concern about air quality had of course been the reason for imposing emission controls in the first place, the degree of emission control that had been imposed had been limited to what was known to be possible of achievement.

The period from passage of the Clean Air Act until now has been a turbulent one. Administrative review procedures in the Act itself resulted in temporary, short-term suspension of the implementation of the statutory emission standards, with stringent interim emission standards. And shortly after those proceedings had run their course, the Arab oil boycott and the subsequent high prices for crude oil initiated new reviews in our country of the schedule for meeting the emission standards for automobiles, as well as new questions of whether the standards should be so stringent as the Clean Air Act made them.

Arguments against the standards focused primarily on their impact on the fuel economy of individual cars. There was a frequent tendency, on the part of those who wanted to scrap the Clean Air Act standards, to ignore the fact that emission controls-- which had indeed through the 1974 model year tended to reduce fuel economy -- had had a far lesser effect on excessive fuel consumption than had other factors.

Of these other factors, weight is the most important one. The relationship of vehicle weight to fuel consumption is just about linear in the city driving. A 5,000 pound car uses about twice the fuel as does a 2,500 car. Fuel economy varies by over a factor of four between the smallest and largest cars available on the American market. Next most important is air conditioning--depending on the temperature and humidity, a car with an air conditioner "on" uses anywhere from 9 percent to 20 percent more fuel than it does without it (and of course the air conditioner adds weight and thus consumes fuel even when it is off). Automatic transmissions increase fuel consumption anywhere from 2 percent to 15 percent, depending on the type of transmission and other factors. Power steering, power brakes, power windows, power seats, and so forth do not significantly add to fuel consumption, except insofar as they add to the weight of the car. In that sense, of course, a vinyl roof and a deluxe chrome trim package also reduce fuel economy.

Emission controls had caused fuel economy losses, on a salesweighted average, of about 10%. But this 10 percent loss was not evenly spread over all cars. Larger cars had lost more--up to 18 percent, while smaller cars, those of 3,500 pounds or less, actually showed a marginal fuel economy improvement. And of course there was promise of a sharp reversal of this on 1975 cars equipped with catalysts.

Fortunately -- from the standpoint of public health -- these data persuaded our Congress not to give in the frantic demands of the industry for the scrapping of the emission control program. Instead, late last Spring the Congress voted a brief delay in the implementation of the statutory standards -- no longer than two years -- and at the same time called on the Environmental Protection Agency and the Department of

Transportation to make a joint study on the feasiblity of improving the fuel economy of cars in the context of applicable emissions and safety standards.

That study was completed and the report was submitted about 10 days ago. It concluded that substantial improvement in fuel economy is possible without giving up the clean air emission standards. The only real question, the report said, is whether the statutory NOx standard can be met together with markedly improved fuel economy--and as regards that standard, the EPA over a year earlier had advised the Congress that the NOx emission standard had been set on the basis of faulty data and should be substantially relaxed for the near-term future.

Opportunities for markedly improving fuel economy, the report states, lie in technological improvements in engines and drive trains, in changes in the weight to power ratios, in reducing vehicle weight without reducing usable vehicle space, as well as in increasing the proportion of small cars in the total vehicle fleet. Using 1974 model year fuel consumption as a base, the report concludes that up to 60% fuel economy improvement in the total new car fleet can be achieved by 1980, and more than that by 1985, without giving up on the statutory emission standards for HC and CO and with more stringent control of NOx than is required on today's cars, though possibly not as stringent as the statutory NOx standard would require.

The report states that these gains can be achieved at acceptable cost. Up to 20% improvement should be possible without any increase in the price of cars. A 30% improvement may add $200 to the new car price, and a 40% improvement will add $400 -- but these higher new-car costs will quickly be recovered through savings in fuel, and will thus represent a net saving in the cost of car ownership.

Industry's reactions to this report -- which is the joint product of the technical staffs of the two agencies that prepared it, and which drew heavily on data provided by the industry -- is not yet in hand. However, it is probable that the auto industry will attack the report as too optimistic and its conclusions as incapable of achievement. This is predictable because that is what the auto industry always says, just as they claimed in the Spring of 1973 that widespread use of catalysts on 1975 models would result in an industrial disaster-- only to voluntarily adopt -- just two or three months later -- catalytic technology on the vast majority of 1975 cars. With catalytic technology, as we all know, dramatic fuel economy gains were achieved on 1975 cars together with sharply lower emissions.

But when the tumult and the shouting about this report dies down, and when the kings and captains of the auto industry depart from their lobbying efforts in Washington, the engineers in Detroit and in Wolfsburg and in Higashi Fuji and in many other cities around the world will show once again that most if not all what their bosses may now be claiming to be impossible can in fact be done.

Controversy will continue to swirl about the issue of automotive emission controls. A recent report to the Congress by our National Academy of Sciences estimates that each year there are 4,000 deaths, and 4 million hospital days, that can be attributed to automotive air pollution. The question of how much protection of the public health is needed -- and how much can be afforded in competition with the achievement of other social goals -- will continue to be debated, and properly so. As more and better data on the adverse effects of automotive air pollutants become available, and as automotive technology develops further, there may be changes in the stringency of automotive emission standards -- in either direction.

But one thing seems clear: The Congress, reflecting the views of the American people, will continue to place a high value on the public health of Americans, and will thus continue to demand that everything possible be done to control emissions and to improve automotive fuel economy. In that context, the Environmental Protection Agency will continue to administer the automobile emission program with primary emphasis on what needs to be done to protect the public health, instead of -- as some urge -- in terms of what can easily or cheaply be done. To us the preferences and convenience of the auto industry are clearly secondary to the achievement of the health objectives that the Clean Air Act has made into a major national goal.

The Canadian Approach to Automotive Emissions Control

A.C. Gullon, Air Pollution Control Directorate, Environmental
Protection Service, Ottawa, Ontario

Introduction

I have always found it simplifies my task considerably to follow the United States representative on panels such as this. After he has explained the U.S. situation I need only compare the two approaches to illustrate what we are doing in Canada.

First of all, in the U.S., EPA is alone responsible for new-car automobile emission regulations, while in Canada these emission regulations are the joint responsibility of the Department of the Environment and the Canadian Ministry of Transport. The actual emission standards come under the Canadian Motor Vehicle Safety Act and accompanying Regulations are administered by the Road and Motor Vehicle Traffic Safety Branch of the Ministry of Transport. Environment Canada does the emission testing and provides technical support for developing new emission standards, test procedures and Regulations.

The only other major difference between our two situations in new-car legislation is that Canada uses a 'selfcertification' process versus the supervised certification which is used in the U.S.

To ensure that the companies are in fact doing a proper job of self-certification we moniter the performance of production vehicles by purchasing the cars that are offered for sale to Canadians. In many cases Ministry of Transport personnel are buying cars directly from the show room floor.

New-car Emission Standards Policies

In spite of these differences in organization and procedure, Environment Canada is in general agreement with most of what EPA is doing in the area of automotive emission control. We recognize that in spite of strong public support for protection of the environment, the average consumer will not dip very far into his wallet for a cleaner exhaust. There is thus no competitive urge among the automobile companies to produce the "cleanest" car. Therefore, if progress is to be made in reducing automobile pollution, governments must set and enforce emission standards which every car must meet. Competition is then restored to produce an economical, pleasant running car, which also meets the government definition of 'clean'.

As people who are somewhat remote from the North American scene you may not be aware that although Canada last year announced emission standards for 1975 that were slightly less stringent than the U.S. Interim Federal standards we have generally tried to parallel the U.S. standards. I would like to make a few comments on what appears to be a distinct lack of originality on our part.

Anyone can learn from his own mistakes; a wise and prudent man learns, wherever posiible, from the mistakes of others. With such a grand example of a developing industrial society just south of us Canadian environmental officials would be shirking their duty if they did not study and learn from the industrial and environmental 'history' being made in the U.S.

However, I hasten to add that we are not so far behind that we can afford to delay if we are to avoid similar air pollution problems. Indeed, in the area of automotive emissions we are uncomfortably close already.

Thus in Canada we do not believe we can afford to wait for situations that have deteriorated to the point of presenting obvious health problems. It has been Environment Canada's policy to promote the application of the best practicable control technology to all emission sources. Although, in many areas and especially in the resource industries, Canada has taken the lead in control technology, this policy has also included the importation of the "best practicable" technology when other countries are leading in a particular area.

As far as automobiles are concerned the U.S. has shown the greatest concern and has taken the lead in automotive emission control. The non-originality of our automobile emission program has therefore been nothing more than an extension of existing Environment Canada policy into the automotive field.

In-Use Vehicles

So far I have talked only about new-car legislation. Attention must also be focused on in-use vehicles if we are going to see a large improvement in air quality in our cities. In the U.S., EPA has proposed transportation controls including gasoline sale limitations, exclusive buslanes on major arteries, and, in critical cases, an almost complete ban on parking for commuters in downtown areas. Many of these controls, if carried out, will produce dramatic changes in the traditional role of the motorcar in the U.S.

Because of the division of federal/provincial responsibilities Environment Canada's role - as far as the control of in-use vehicles is concerned - will be limited to acting as an "information reservoir" on the pros and cons of the various mechanisms for reducing emissions from in-use vehicles and/or reducing the number of vehicle miles travelled within a given area. Here again, we will be watching with close attention as U.S. government agencies attempt to coax and coerce the average citizen out of his automobile and onto more environmentally acceptable modes of transportation.

Technical Notes

Much criticism from various sources has been made of the U.S. motor vehicle emissions control program both from within and from outside the U.S. borders. Because Canada has adopted a parallel course we have been subject to the same criticisms I would like to point out however, that the basic technical precepts of the U.S. program are very sound.

In the first place they have chosen to establish an emissions performance standard rather than regulating hardware. In this way they avoid dictating the use of expensive and/or obsolete hardware.

Secondly they have based the standard on the product of the regulated operation ie. vehicle miles travelled. This facilitates comparison of abatement strategies and is an easily understood measurement even to the layman.

Thirdly they have recognized the contribution of the "cold start" and other transient odes to motor vehicle emissions and have included them in the test cycle.

Last, but not least, they have devised an accurate means of measuring the true mass of pollutants emitted; thus making it possible to have a very democratic standard. The manager driving a "Grosser Mercedes" or a Cadillac, or a Rolls Royce to work in the morning is not permitted to pollute any more per kilometer travelled than his employee driving a Volkswagen.

Incidentally this last point also makes for harmony between emission control and energy conservation. No adjustment is made to the standards to allow for the fact that heavier cars must use more fuel, and thus, as any emissions research engineer will tell you, the U.S. emission standards exert significant pressure on the industry to produce lighter automobiles.

Closing Comments

In closing I would like to repeat a thought I expressed a year ago at a meeting in Denver, Colorado. The dream of the "private automobile" in the broadest sense, a faithful servant standing ready to transport us quickly, cheaply, and comfortably, at our whim, to wherever we may wish to go, is a very powerful one. In a very few years, however, man's industry and ingenuity have turned this dream into a reality, and then that reality into a nightmare of highway slaughter and foul air.

The task now immediately before us, and on which we have a very good start, is to reverse the process and turn this nightmare back into a reality we can accept. If we as citizens, legislators, administrators, and members of the automotive industry carry out our responsibilities in the task, then that "acceptable reality" may not be so very far away. It will then only be necessary to change that acceptable reality into the dream of instant mobility that started the whole process in the first place.

Statements by Heads of Delegations on the [illegible] Evaluation Organization

Commission of the European
Communities – H. Schuster (46)

Netherlands – L.C. van Bueren (50)

United Kingdom – D. Dewar (53)

Federal Republic of Germany
– F. [illegible] (55)

Statement presented to the 2nd Symposium on LPPSD at Dusseldorf by
M. VERDIANI, as leader of the delegation of the Commission of the
European Communities

I would firstly like to thank the government of the Federal Republic of Germany for having invited the Commission of the European Communities to participate in this second Symposium on the development of low pollution propulsion system.

The profound interest of the subjects under consideration and the particularly delicate situation through which we are passing at the moment, both in respect to the production of cars as well as their fuel supplies, leaves us to hope that the ideas and conclusions of this Symposium will be able to help us continue to carry out an effective policy for the reduction of nuisances caused by automobiles.

On the European plane, through its legislative action the Commission of the European Communities has always sought to apply the strategy of the "best practicable means" namely by fixing the limits of emission in applying to their sources the best available control technology giving the highest cost/benefit return.

With respect to motor vehicles this legislative activity is carried out according to the procedures established by the Council of Ministers of the Community in February 1970 in its framework directive dealing with the "type approval" of motor vehicles. By this means it was possible - in March of the same year - to introduce in all the countries of the Community a uniform control of emissions of CO and HC, which was - in May 1974 - made more severe.

When the Council has adopted, we hope in the very near future, the other draft directives which the Commission has proposed, we will have in Europe a uniform system of regulations which can be rapidly adapted in order to take into account the evolution of techniques and levels of pollution.

In order that this adaption should be up-to-date and should not introduce distortions into the social and economic structure of our Member States, we base it to the greatest possible extent on the results of international organisations, including the rules of the ECE at Geneva. There is a fundamental difference of approach between the Community, whose directives oblige the Member States to introduce technical specifications in their national legislation, and the ECE at Geneva which propounds which are basically voluntary in application. For this reason states, mostly European, apply ECE rules and we can use them only as a source of technical information.

The services of the Commission are, therefore, deeply engaged in this field with the aim of gathering on an international plane objective information related to the evaluation of the effects of different pollutants on human beings and on the environment.

These studies and the research programmes which are being carried will enable the working groups of the Community to choose the most effective way of evolving common regulations as quickly as possible, so that criteria and norms for air quality may be established which give the best protection to human health and the environment.

The strategy to be applied in the future must take into account those developed, we hope equally on a common basis, for a rational utilisation of energy sources, and, in this respect, several approaches are possible. One important, if not fundamental decision, will be to determine if in an economy of shortage of petroleum and natural gas it would be more effective to give priority to the production of electrical energy from coal and nuclear reactors, reserving the use of petroleum products for transport, or if the contrary solution would be valid at the expense of the internal combustion engine.

For these reasons the Commission is paying particular attention to the results of this Symposium.

Exhaust Emissions Legislation in the Netherlands

by Ir. L.C. van Beekhoven

Ministerie van Volksgezondheid en Milieuhygiene

As to the exhaust emissions legislation in the Netherlands in force at present, I can be brief; we follow the E.C.-regulations on gasoline and dieselengined vehicles. This leaves out the small motorcycles for which we are working on emission standards.

The future situation: under the present E.C.-rules the total emissions of hydrocarbons and carbonmonoxide in 1987 are expected to be only slightly lower than in 1970, whereas oxides of nitrogen will more or less double. All because of the expected growth of traffic. With NO_x actually the situation is worse, because the predicted growth of total fossil fuel combustion is larger than that for traffic alone.

The main air pollution problem in the Netherlands, related to traffic, is photochemical smog formation. In 1965, 1968 and 1971 we have had periods of fairly high oxidant levels. During the past three years levels have been relatively low. This however is an indication that meteorological conditions have been favourable. The potential for smog formation is in fact growing continuously.

My government considers drastic reduction of all vehicle emissions a necessity, this means CO, HC and NO_x.
Such emission reductions will have to be balanced against the effects on society as a whole. In this respect NO_x-emissions seem to be among the more difficult ones, as up till now a clear relationship with fuel consumption seems to exist. However, there are indications that the development of a clean engine with good fuel economy need not be a fiction.

One related problem I would like to briefly mention: it seems that drastic reduction of total NO_x-emissions cannot be obtained under the E.C.-test cycle conditions.

In the future it must be possible to produce engines that are clean under all operating conditions.

In this respect we are happy to see in the programme of this symposium papers on promising developments both of the conventional and of the unconventional power plants.

Statement by Head of UK Delegation
Exhaust Emission Legislation

1. Petrol engined vehicles

a. Hydrocarbons and Carbon Monoxide Controls over the emission of hydrocarbons and carbon monoxide by petrol engined vehicles were introduced in the United Kingdom in November 1973 when compliance with Regulation 15 of the United Nations Economic Commission for Europe (ECE 15) or EEC Directive 70/220 became a statutory requirement. The 01 series of amendments to Regulation 15 and EEC Directive 74/290 (which introduce lower limits for HC and CO emissions) will become effective in UK in October 1976.

b. Nitrous Oxides There ist currently no control over the emission of NOx by petrol engined vehicles in UK. If it seems likely that the level of NOx emissions will encrease as a result of the introduction of the lower limits for HC and CO then the UK could agree to a holding limit for NOx on the lines now being discussed in ECE.

c. Lead There are no statutory controls on lead emissions from motor vehicles in UK at the present time. However an agreement has been reached between the Government and industry to reduce the lead content of petrol to 0.55 grams/litre with effect from 1 November 1974. The position is to be reviewed again in 1975 taking into account any new evidence which becomes available on the health aspects of lead emissions and the implications which further lead reductions may have on the energy situation and the national economy.

2. Diesel engined vehicles

The United Kingdom has no legislation for limiting the exhaust emission from diesel engined vehicles other than for the control of smoke. Since April 1973 all diesel engines fitted to new motor vehicles must be of a type which has been certified to the British Standard for the Performance of Diesel Engines BSAU 141a. Approval to EEC Directive 72/306 gives exemption from the requirements of UK regulations for controlling the emission of smoke from new vehicles but as this Directive does not have a linked power measuring requirement approval to BSAU 141a is still required to meet the power to weight regulations for diesel engined vehicles which are mandatory in the United Kongdom.

3. General

In general the United Kingdom could not willingly accept any more stringent air pollution controls until the results are available of the studies now being carried out by the EEC Expert Groups on criteria studies. These Groups are to define air quality objectives upon which future air pollution legislation can be based and until these objectives are known, and the need for emission controls has been related to them, the United Kingdom prefers to maintain the present position.

Statement of the Delegation of the Federal Republic of Germany Concerning Exhaust Gas Legislation

Ministerialdirigent P. Menke-Glückert,
Federal Ministry of the Interior

In the Federal Republic of Germany, environmental protection continues to be considered as a priority task. Health protection is one of the chief demands. Should we, for instance, once come to the conclusion that certain compounds of the exhaust gas are carcinogenic, it will probably be too late. We should always keep in mind the dangers caused by PVC production which have become known only recently. It is, therefore, not sufficient to restrict our activities to the present level of knowledge.

In our society, the motor vehicle has become a standard and favourite property of all classes. Owing to the increasing motorization during the past twenty years, however, the motor vehicle has become a problem. Government, industry and population - they all agree that problems have to be solved.

In its Envirionmental Programme of autumn 1971, the Federal Government has therefore stated its intention that it would aim at reducing, by 1980 and step by step, exhaust emissions of Otto engines to one tenth of the average rate of 1969. These values are nearly as stringent as those planned in the USA for 1977, whereby it has to be indicated that - owing to the different testing and measuring procedures - these values are not really comparable. In this context, I would like to point out that, in my opinion, it would be advisable to make attempts to standardize these procedures on a world-wide level.

Already in August 1971, the Gasoline Lead Law was passed by our Parliament. At a second stage, from January 1, 1976, the concentration of lead compounds in petrol will be reduced from 0,4 gr/l to 0,15 gr/l. Once the objectives pursued for 1980 will be accomplished, it will however - from a technicalpoint of view - hardly be purposeful to formulate more rigorous provisions for reducing exhaust emissions since this would increase the costs so enormously that the car would become a luxury article which only a minority could afford.

According to the recommendations submitted by the Council of Experts on Environmental Problems, further improvements may be realized through an integrated traffic planning. Future activities will have to concentrate on this issue. Long-term traffic planning is the most important instrument for organizing the individual traffic in conformity with environmental demands. Projects for enlarging the existing systems of road, railway, air and inland water traffic will have to be harmonized. It is absolutely necessary to initiate an integrated traffic planning which, along with the other specialized projects, will be embedded in a superior global planningsystem, and which will consider the different individual traffic facilities as more component parts of a total traffic system.

The individual traffic will have to be reduced where its impacts exceed certain threshold values. In town-centres, for instance, appropriate areas should be blocked and changed into pedestrian zones. At the same time, the public transport facilities should be rendered more attractive.

In the future, much more importance will have to be attached to the problems of traffic noise abatement. In this field, considerable emissions have to be recovered. The Federal Government intends, therefore, to reduce the noise standards for motor vehicles by at least 5 dB (A), and for trucks by at least 10 dB (A).

Opening of the Exhibition and Presentation of Electric Busses to the City of Düsseldorf

Ministerialdirigent Dr. W. Finke	(FI)
Oberbürgermeister K. Bungert	(BU)
Dr.-Ing. H.G. Müller	(MU)

Description of Exhibits

The contribution of the description of exhibits were written by the exhibiting companies, the contribution of the USA excepted.

Opening of the Exhibition
by Ministerialdirigent Dr. W. Finke, Federal Ministry for Research and Technology

Ladies and gentlemen,

At the close of this morning's programme, it is both an honour and a pleasure for me to open the Exhibition devoted to advanced and new-type power systems and components for motor vehicles. I am happy to convey to you the greetings of the Federal Government.

Above all, I should first like to thank the NATO Committee on the Challenges of Modern Society - a Committee which studies the social problems of modern society - for honouring us with the request that we organize the 1974 Symposium on the Development of Low Pollution Power System in the Federal Republic of Germany. We assumed this task willingly, since we are also affected to a large extent by the problems posed by motor vehicles.

Permit me now to elucidate for the experts from all parts of the world assembled here today some of the aspects of the means of transportation, the motor vehicle, and to outline briefly the objectives under government research and technology policy in the field of transport.

In every industrialized society, the private motor vehicle occupies a high place in the possessions of people at all levels of society. The mobility provided by the motor vehicle has decidedly bettered man's economic and social standing. Major impulses have resulted from increasing motorization leading to changes in all sectors of life:

- In coping with tasks in the sector of traffic and transport in urban and long-distance transportation systems, the motor vehicle occupies a dominant position.

- The influence of the motor vehicle has brought radical changes in the location of residential and settlement areas, industry, trade and commerce.

- In the business and private sectors, the automobile has helped to improve communications. In addition, it has considerably increased the possibilities for our citizens with regard to leisure-time and vacations.

On the other hand, road transport - not only in the Federal Republic of Germany - has had considerably adverse effects on man's environment during the past few years:

- The automobile is the cause of emissions of all kinds: exhaust gas, noise and wastes.

- In view of the long-term energy forecasts, energy requirements are cause for concern if energy is used in an uneconomical manner.

- Of all means of transportation, the automobile constitutes the greatest threat to life, health and property.

- The demand for highways is excessive and therefore creates problems for social and policy planning.

Our conurbations, in which almost half our population lives, are particularly affected by the negative consequences of increasing motorization.

We must not accept these facts as inevitable. The weak points in this development must be abolished by joint endeavours on the part of government, society and industry. Legislative and organizational measures by themselves do not suffice. It is therefore an important task under government research and technology policy that the specific problems and needs of the population and our community be recognized and the developments of vital importance to the life of mankind be intensified by way of systematic promotion measures.

Of course, it is certainly right that a priority task of the government is the promotion of technological developments for the improvement of existing means of public transportation and the designing of new-type methods of conveyance. Public transport must be made more attractive, since the aim under our present market economy, namely freedom of choice of means of transport, entails to an increasing extent the abandonment of goals in other sectors.

However, the automobile is still - and will, in the forseeable future, remain - the method of transport best suited from the economic and technical point of view for multi-purpose use. It has had such an effect on the location of settlements, people's behaviour and the economic structure of our country that an abrupt change would bring incalculable consequences in its wake.

We use the automobile today, and we shall still need it tomorrow. New transport systems cannot be regarded as substitutes either within a short-term period or a longer term. This is all the more reason why we must press ahead with research and technological development in the interests of producing a low pollution, safe motor vehicle requiring a small amount of fuel. Up to now, these tasks have been attempted on the one hand by those branches of industry involved - either in anticipation of, or in response to, changing market requirements or customers' wishes - whereas on the other hand they have often been tackled only under the pressure of legal regulations.

Government promotion for research and technological development aimed at improving both motor vehicles and road transport must actively contribute towards the achievement of this goal. Such promotion supports necessary but risky new designs by way of systematic measures, and is intended to present the possibilities of technical improvements. Promotion does not end with theoretical studies. Prototype designs and conclusive demonstration projects constitute the next stages before reliable assessment criteria can be established. To date, we have provided DM 20 million for promotion measures in the field of vehicle and traffic technology. In future, we shall have to increase our efforts even more in this field.

We are confronted with a task which cannot be studied without examination of corresponding developments in other countries. Close interrelations in the world economy require a constant comparison of that which has been achieved with developments in all parts of the world. Bad designs must be corrected in good time. The progress which we make today in technological research and development is the basis for industrial development tomorrow. In this respect, joint endeavours are required on the part of all those involved.

This first international exchange of experience in the Federal Republic of Germany concerning both improved and new-type motor vehicle power systems is a milestone in the worldwide endeavours to design better motor vehicles. The various development priorities in the individual countries will be discussed. At the same time, the Exhibition enables visitors to acquaint themselves with the prototypes of power systems and to actually see how they work in operation. I hereby extend an invitation to all those members of the public who are interested, to inform themselves on the spot with regard to the international level of development.

After these remarks, for the second time within the space of a few weeks, buses operation on electric batteries will be handed over to a public transport company for trial runs under near-normal operating conditions.

The testing of buses operating on electric batteries on regular public transport routes is an experiment which is being promoted by the Federal Minister of the Interior, Land Northrhine Westphalia and also by the Federal Minister for Research and Technology. The electric vehicle on the road has not been able to demonstrate its practicability. The system is as yet by no means ready for the market. Its strong points, and its weaknesses, must be carefully analysed during practical tests and compared with rival designs. The project will yield further knowledge concerning the prospects for electrically-driven vehicles. I hope that the tests will be successful and that we shall gain the information necessary before further decisions can be taken in this respect.

I also wish you success in the discussions scheduled on the programme of this Symposium and, like you, anticipate the strengthening of international contacts and a fruitful exchange of experience, which we all need and from which we shall all profit.

Übergabe von Elektrobussen an die Rheinische Bahngesellschaft
durch die GES am 4.11.1974

Klaus Bungert,
Oberbürgermeister der Landeshauptstadt Düsseldorf

Hochverehrter Herr Bundesminister,
Herr Ministerialdirigent,
sehr geehrter Herr Dr. Müller,
meine sehr verehrten Damen und Herren,

ich habe die große Freude, in diesem Augenblick von der Gesellschaft für elektrischen Straßenverkehr drei Busse in die Obhut der Rheinischen Bahngesellschaft übernehmen zu dürfen, die den Vorstellungen von einem umweltfreundlichen Verkehrsmittel - so meine ich - in hohem Maße entsprechen.

Das Thema Umweltschutz ist in jüngerer Vergangenheit erst als eines der zentralen Probleme unserer Zeit erkannt worden. Zu lange ließen wir uns blenden von technischem Fortschritt und wirtschaftlicher Expansion. Zu lange haben wir übersehen, daß der daraus resultierende Wohlstand der Industrienationen eben auch eine sehr gefährliche Kehrseite hat. In zunehmendem Maße sind wir Einflüssen ausgesetzt, die unsere Gesundheit und unsere Umwelt zu zerstören drohen oder bereits zu zerstören begonnen haben.

Welcher Art diese Gefahren sind, brauche ich in diesem Kreis nicht zu erläutern. Wie ernst sie inzwischen genommen werden, das zeigt nicht zuletzt auch das heute morgen eröffnete NATO-Symposium und die damit verbundene Informationsschau. Sie befassen sich mit einem wichtigen Teilaspekt des Umweltschutzes - nämlich der Luftreinhaltung.

Neben der Industrie ist für die Luftverschmutzung das Kraftfahrzeug zweifellos eine der Hauptursachen. Wie dieses Verkehrsmittel von diesem Makel möglichst weitgehend befreit werden kann, das ist Gegenstand der Erörterungen in diesen Tagen. Wie das in der Praxis zu verwirklichen ist, das demonstriert für einen Teilbereich des öffentlichen Personennahverkehrs dieser batteriebetriebene Bus.

1972 waren in Düsseldorf bereits zwei Prototypen dieses zukunftsorientierten Verkehrsmittels versuchsweise im Einsatz. Die dabei gewonnenen Erfahrungen waren recht ermutigend. Nicht nur, daß dieses Fahrzeug völlig abgasfrei ist. Es zeichnet sich darüber hinaus auch durch eine fast geräuschlose, gleichmäßige und erschütterungsfreie Fahrweise aus. Die lärmgeplagten Anwohner, die Fahrgäste und nicht zuletzt auch die Fahrer dürften diese Eigenschaften mit besonderer Genugtuung registrieren.

Die insgesamt 13 Elektrobusse, die Düsseldorf bis zum kommenden Frühjahr erhalten soll, werden im Süden der Stadt auf den Linien 39 und 62 eingesetzt werden. Zumal die Linie 39 führt im Bereich des Stadtteils Garath überwiegend durch reine Wohnstraßen. Hinzu kommt, daß diese Linie zu den Hauptverkehrszeiten im 7 1/2 bzw. im 10 Minuten-Takt verkehrt. Um so mehr bin ich überzeugt, daß der Einsatz dieses umweltfreundlichen Fahrzeuges gerade auf dieser Strecke als eine wesentliche Entlastung empfunden wird. Man wird darin einen nicht zu unterschätzenden Beitrag auch zum Thema "Menschliche Stadt" sehen dürfen.

Saubere Luft und Geräuschlosigkeit haben in diesem Falle vorerst sicher ihren besonderen Preis. Im Rahmen einer Vereinbarung werden die hohen Investitions- und Betriebsmehrkosten hier aber voll von der GES übernommen.

Meine sehr verehrten Damen und Herren,
ich möchte nicht verfehlen, der bei diesem Projekt federführenden Gesellschaft für elektrischen Straßenverkehr und allen mit ihr an der Entwicklung dieses nicht nur umweltfreundlichen, sondern auch energiebewußten Verkehrsmittels beteiligten Firmen ein Wort herzlichen Dankes und der Anerkennung zu sagen.

Dank gebührt sicher auch den zuständigen Bundes- und Landesministerien, die mit ihren Zuschüssen dieses Vorhaben verwirklichen helfen.

Wir freuen uns, daß die GES, die von der Rheinisch-Westfälischen Elektrizitätswerk AG eigens zur Lösung aktueller Energie- und Umweltprobleme gegründet wurde, ihren Sitz in Düsseldorf hat. Wir freuen uns ganz besonders, daß die Landeshauptstadt bzw. die Rheinische Bahngesellschaft zusammen mit der Stadt Mönchengladbach an diesem erstmalig durchgeführten, groß angelegten Modellversuch dieser Art beteiligt ist. Wir hoffen, so mit Schrittmacherdienste leisten zu können für ein Projekt, das nicht nur neue und zukunftssichere, sondern auch in jeder Hinsicht umweltfreundliche Antriebsenergie erschließen helfen soll. Ich vertraue hierbei auf eine gute Zusammenarbeit zwischen allen Beteiligten und wünsche dem Modellversuch zugleich einen vollen Erfolg.

Nochmals herzlichen Dank.

Übergabe von Elektrobussen an die Rheinische Bahn-Gesellschaft

Dr.-Ing. H.-G. Müller, Gesellschaft für elektrischen Straßenverkehr mbH.,
Düsseldorf

Sehr geehrter Herr Minister,
sehr geehrte Damen und Herren,

mir wird die Ehre zuteil, überzuleiten auf eine Episode am Rande dieses Symposiums.

Ich meine, es verdient Beachtung, wenn in viele Worte eine Tat eingebettet ist. - Erstmalig in der Welt realisieren wir mit dem Modellversuch "Elektro-Bus in Nordrhein-Westfalen" die Ablösung von 20 Diesel-Omnibussen auf drei Linien des öffentlichen Nahverkehrs durch fast perfekt umweltfreundliche, von Öl-Krisen unabhängige batterie-elektrisch gespeiste Fahrzeuge! Dies ist ein Schritt evolutionärer Ingenieur-Arbeit. Wir haben Bewährtes neu kombiniert und dabei gelernt, daß auch dies zu neuer Technologie führt. Diese hat aber vor anderen Entwicklungen den Vorzug, daß sie überschaubar bleibt ebenso in der fortschreitenden technischen Erkenntnis wie in der wirtschaftlichen Realisierbarkeit.

Der Omnibus ist ein Auto, das unter besonders extremen Fahrbedingungen betrieben wird. Deshalb werden wir durch diesen Versuch besonders viel für die Entwicklung kleinerer Fahrzeuge lernen können. Letzteres tut Not, denn der Bürger braucht flächenorientierte Individualfahrzeuge als wichtiges Mittel zur Mobilität, vor allem in engerem Lebensraum. Auch für Ihre Kinder und Enkel, meine Damen und Herren, gilt dies! Erölderivate aber wird es in einigen Jahrzehnten kaum noch geben. Als Subsitut gilt heute Kernenergie und Kohle; Elektrizität als die verbindende Sekundärenergie ist nicht nur umweltfreundlich, sondern bietet auch die zugehörige Verteilungsinfrastruktur, die wirtschaftlich ist, weil sie vielfältig im Verbund genutzt wird.

Unser Programm - darauf sind wir stolz - entspringt vorwiegend privatwirtschaftlichen Initiativen der Automobil-, Elektro- und Elektrizitätsversorgungsindustrie. Es fand die Förderung von Ministerien des Bundes und des Landes. Ihr Haus, Herr Dr. Dreyhaupt, stellte Bonn hier - leider - bei weitem in den Schatten.

Ohne den Schritt in die Praxis, und das heißt ohne den mutigen Erstanwender kann sich kein technischer Fortschritt entwickeln. Mit 2/3 aller E-Busse übernimmt das Verkehrsunternehmen von Düsseldorf, die Rheinbahn, die Schwerpunktfunktion dieses Großversuches. Sie, sehr geehrter Herr Oberbürgermeister, repräsentieren als Aufsichtsratsvorsitzender dieses Unternehmens dessen technischen Mut - Herr Direktor Scheucken und seine Männer werden Erfahrung und kritisches Betriebsbewußtsein beitragen - sie handeln aber auch für die Bürger dieser Stadt, die aufgeschlossen für zukunftsgerichtete Neuigkeiten mit uns den Weg durch die obligaten Kinderkrankheiten gehen sollen.

Mein herzlicher Dank gilt Ihnen allen, den Stimulatoren wie den Förderern.

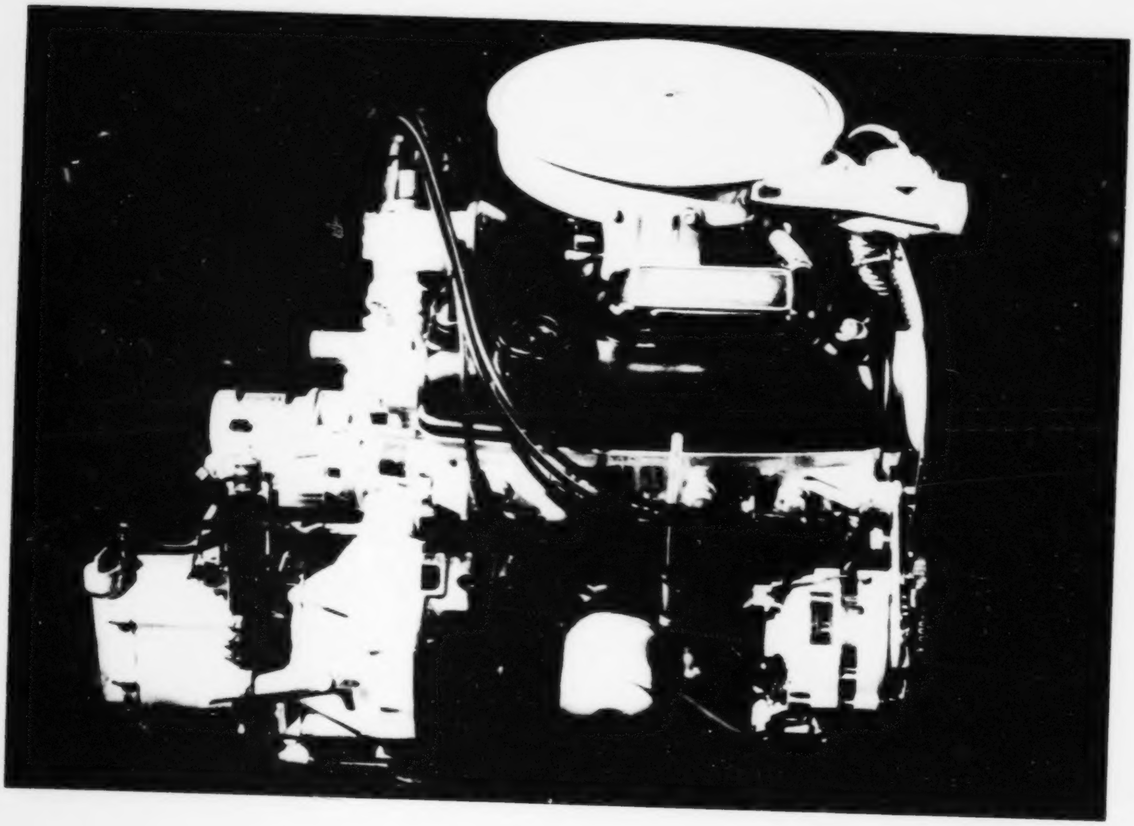
HONDA CVCC Engine

HONDA presented on CCMS Symposium-Exhibition at Düsseldorf stratified charging Engine with HONDA developed CVCC Combustion system.

The cut-Engine demonstrated carburator system and position of pre and auxiliary combustion chambers.

Besides that, the function of Engine Combustion was again shown on the explanatory board.

On another board the measurement datas of HC, CO, NO_x and fuel consumption was shown. The datas were determined by EPA.



HONDA
CIVIC CVCC

DESCRIPTION OF THE PHILIPS STIRLING STAND

The Philips Stirling stand had a double aim, namely

1. To give a comprehensive survey of research and development work of the Stirling engine at Philips which has lead to the cooperation between Ford U.S.A. and Philips.
2. To emphasize the possibilities of the Stirling engine (by its main features like high efficiency, multifuel capability, low noise and low or even no emissions) to contribute to the solution of many demands (like pollution reduction and energy conservation) of modern society.

For this purpose the following engines and/or components have been exhibited and/or demonstrated in operation:

1. A Stirling engine of about 1900, according the patent of Robert Stirling (in operation).
2. A demonstration model of the rhombic drive (1).
3. A demonstration model of the operation of the rollsock sealing system.
4. Some heater assemblies of several types of Stirling engines.
5. A 4 kW Generator set powered by a single cylinder Stirling engine with rhombic drive (in operation) (2).
6. A garden tractor, equipped with a single cylinder 7 BHP Stirling engine with rhombic drive (in operation) (3).
7. A demonstration model of the swashplate drive for double acting multicylinder Stirling engines.
8. The first experimental double acting Stirling engine with swashplate drive; power rating 60 BHP (4).
9. Several photographs of the 170 BHP 4 cylinder double acting Stirling engine with swashplate drive. This engine has been built within the framework of the Ford-Philips cooperation and will be tested in a Ford Torino car in the beginning of 1975. With this engine it has been proved that the Stirling engine can compete with gasoline engines with respect to engine weight and volume (5).
10. The multifuel capability of the Stirling engine was demonstrated by a 10 Watt Stirling engine heated by a heat storage. The heat storage material is a eutectic fluoride salt mixture. The charging and discharging of the heat accumulator is performed with the aid of a heat pipe. The accu-

mulator is insulated by a multifoil superinsulation.

11. The Stirlingbus (6).

    The Stirlingbus is equipped with an experimental 4-cylinder in-line Stirling engine; presently developing 100 BHP. This engine is currently being uprated to 150 BHP. The bus made daily demonstration tours on the exhibition area.

12. In a demonstration and projection room films and slides of the operation and application of Stirling engines were shown. Also in this room the 4 cycli Stirling demonstrator was in operation. With this demonstration machine the four operation modes of the Stirling process were shown namely

    1. Cryogenerator (-200°C)
    2. Cold gas Stirling engine
    3. Heat pump (+ 650°C), and
    4. Stirling engine.

(1) See Fig. 4 of Paper "The Potential of the Philips Stirling Engine for Pollution Reduction and Energy Conservation" by R.J. Meijer and C.L. Spigt, 2nd Nato-CCMS-Symposium, Düsseldorf, Session 3.

(2) See Fig. 5 of the above mentioned paper

(3) See Fig. 7 of the above mentioned paper

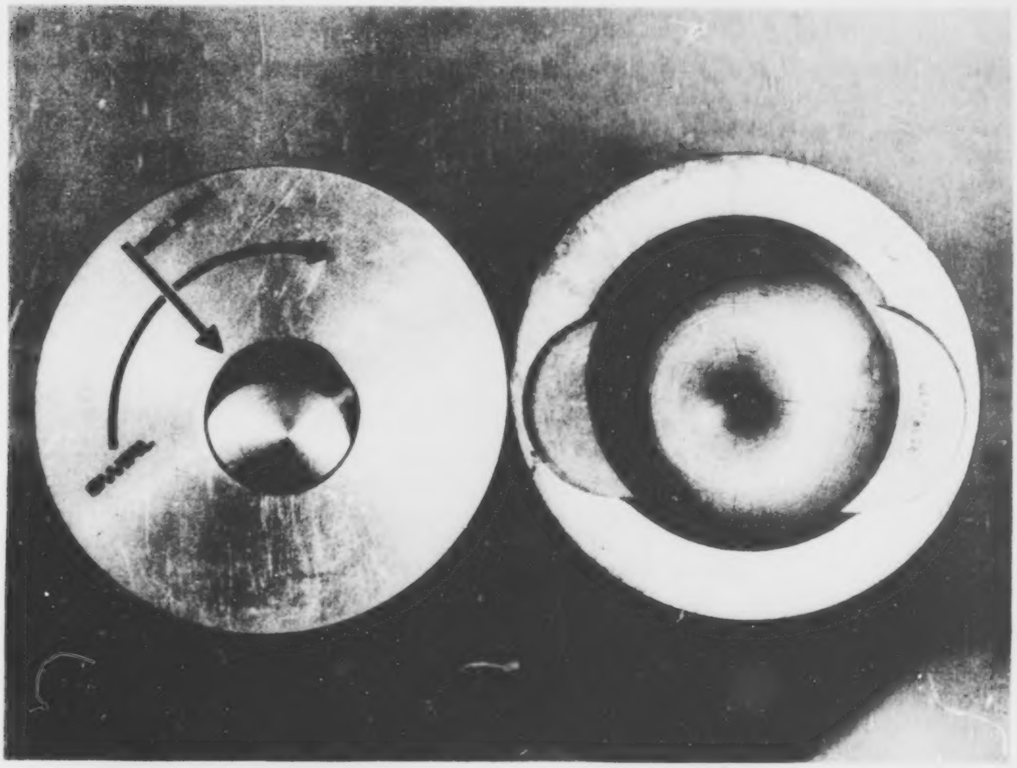
(4) See Fig. 12 of the above mentioned paper

(5) See Fig. 13 of the above mentioned paper

(6) See Fig. 9 of the above mentioned paper.

A cut-away Perkins type D 3.152 diesel engine, fitted with the SQUISH LIP piston and matching fuel injection equipment, was exhibited on the Perkins stand at the NATO - CCMS 2nd Symposium in Düsseldorf.

Engine performance curves and a short description of how the Squish Lip Combustion System operates were also on display. These were supplemented with samples of cylinder head, pistons and valves from an engine having completed over 1000 hrs. endurance testing.

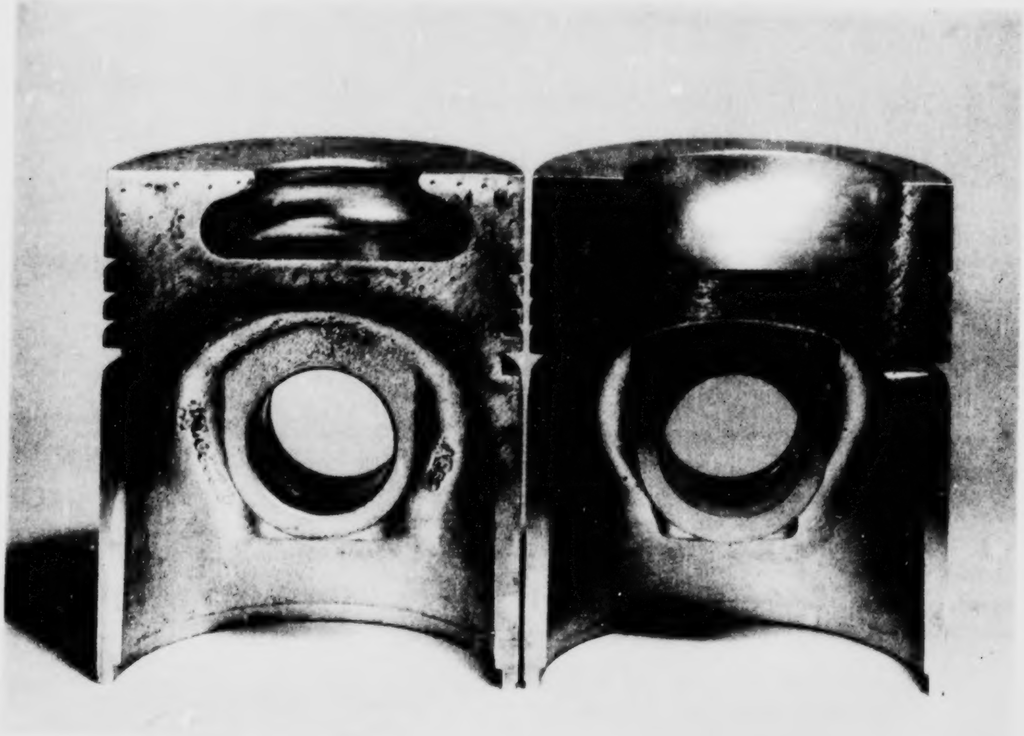


Comparison of Squish Lip (left) and standard piston faces.

Perkins research proved that a low - profile heat release diagramme with late optimum timing can be obtained from a direct-injection engine by combining a high inlet port induced swirl with turbulence generated from squish (piston motion induced) flow.

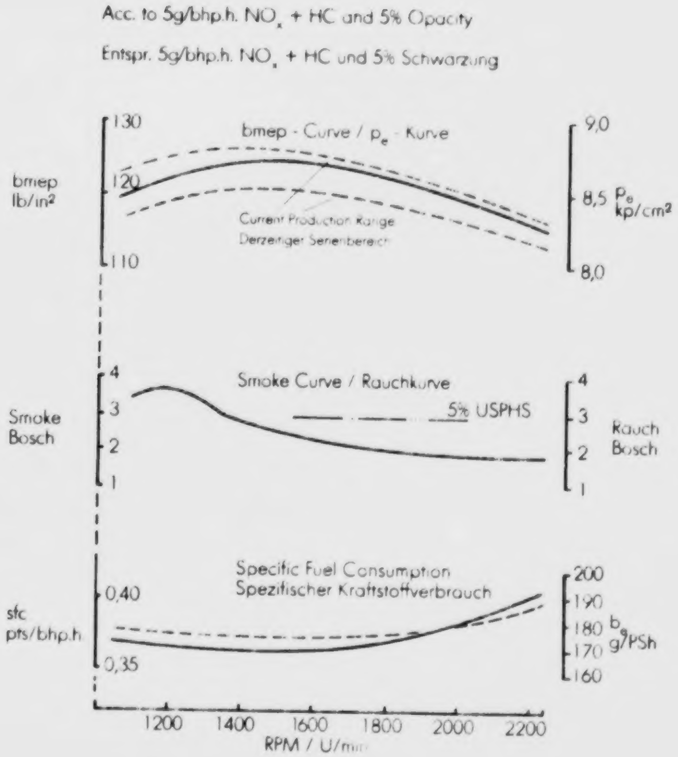
The improved exhaust quality is achieved by faster air/fuel mixing followed by a "rich" combustion stage in a wide throat chamber in the piston head.

A circumferential lip is formed as part of the piston crown toroidal cumbustion chamber. The combustion products are mixed with air trapped above the piston in a vigorous air swirl.



Comparison of Squish Lip (left) and standard bowl geometries.

The Perkins Squish Lip yields major reductions in both oxides of nitrogen and smoke. The new system has allowed gas emission levels under laboratory conditions below 5 g/bhp.h. NO_x + HC to be attained on the 13-mode California cycle at improved smoke levels.



Performance Curve of a D3.152 'Squish Lip' engine.

With this combustion system reduction in noise levels averaging 3 dB(A) at 1 m (a 50 % reduction) have been recorded. This is because the system is characterized by low rates of pressure rise, which means that the bare engine noise levels are greatly reduced. It results in a softening of the "diesel knock".

A further benefit is that the Squish Lip System is not very sensitive to fuel quality - a factor which will become more important in the future with the growing world fuel crisis.

Stand of the USA

Four fully operational experimental vehicles, two engine mock-ups, various components and several demonstration tables were exhibited. The four vehicles described below could be used for demonstration drives.

A Ford Capri, model 1973, was equipped with the prototype of a stratified charge engine, which has been developed for order of the EPA by the American Ford Company. The stratified charge engine provides the advantage of a reduced emission of pollutants at a less susceptible reaction against low-octane gasoline (e. g. unleaded gasoline).

The two sedan cars "Dodge Coronet" and Plymouth Satellite" were driven by a Chrysler gas turbine engine. The advantage of the gas turbine, apart from its smooth run and exhausts with a low content of noxious matter, is its driving performance of more than 300,000 km achievable at almost negligible maintenance work, and a further asset is the large number of fuels that can be burned in the turbine. At present, the gas turbine engine is being developed further in cooperation with NASA and it is intended to be mass-produced in a compact car.

The electric vehicle 512 of General Motors offers room for two passengers. Its exterior body is of fiberglass, and it has a steel chassis floorpan and weighs 567.5 kg, including batteries (84 Volts). The car is equipped with a Delco-Remy motor and has a range of 90 km at a speed of 40 km/h and of 75 km at a speed of 50 km/h. Acceleration from 0 to 50 km/h is 12 seconds. Complete recharge of the batteries takes 7 hours.

Furthermore, two engine mock-ups were exhibited. A passenger car front part was equipped with a Rankine cycle engine. The second mock-up consisted of a drive block with gas turbine, gear and drive wheels.

Moreover, various components of the Rankine system and of the gas turbines were shown, e. g. turbine wheels, compressor wheels, boilers, turbines, turbine expanders, reciprocators etc.

The information was supplemented by a number of demonstration tables.

Audi NSU Ro 80 Sedan with Rotary Engine

The production of the Ro 80 car with today's design and with an improved and further developed rotary engine has been started in 1967.

The most interesting part of the Ro 80, the two-bank rotary engine with 2 x 497 cm^3 chamber volume has an output of 115 HP (DIN) at 5500 1/min.

This engine shows the following advantages compared to the conventional reciprocating engine:

- less vibration
- lower noise level
- lower weight
- smaller volume
- less parts (no valves)

Since its introduction in 1967, this engine has been improved continuously and the durability has been increased to 100 000 km and more until today.

Since October 1971, the Ro 80 rotary engine is equipped in series production with an exhaust emission control system. It has been proved to be advantageous, that the higher exhaust gas temperatures compared to those of the reciprocating engines, allow a reduction of hydrocabon and carbonmonoxide by a thermal reactor system. Furthermore, the emission of NO_x is basically already low.

The rotary engine with its relative short development time has still a large development potential.

Remarkable progresses have been and will be achieved in the following development areas:

- Reduction of fuel consumption
- Exhaust emission control
- Reduction of production cost.

-o-o-o-

The efforts of Bosch with respect to cleanliness of exhaust gases and economy of fuel consumption in motor vehicles have been directed particularly toward further development of petrol injection and ignition systems.

In 1967, the D-Jetronic system in which the absolute pressure in the intake manifold is the main parameter for system control went into series production. It was the first important electronic device put into mass production for application in vehicles. Up to now, about 2 million such devices have been produced for about 20 different vehicle types. With this system it was in the past possible to comply with the requirements of the exhaust gas regulations of the USA and Europe. Recently, the D-Jetronic system has been replaced by the L-Jetronic system where the quantity of air is measured. This system makes it possible to compensate changes in the engine characteristics, which may occur during the life of the vehicle, automatically and ensured therefore maintenance of good quality of the exhaust gases. In addition, a mechanical petrol injection system - the K-Jetronic - based also on air quantity measuring and operating without mechanical drive has been introduced on the market. The principles of operation of both systems were shown on displays and with sectional models.

In order to be able to meet also future still more severe exhaust gas regulations Bosch has developed the so-called Lambda-Sensor. By this device it is possible to measure the quantity of free oxygen in the exhaust gases. The output signal of this sensor is used to regulate the air-fuel ratio of the mixture by controlling the carburetor or the injection system, and thus contributes to further reduction of the emission of harmful substances in the exhaust gases. With this Lambda-Sensor economical systems for clean exhaust gases can be realised effecting nearly complete conversion of the CO, HD and NO_x components of the exhaust gases in conjunction with a single-bed catalyst. In order to ensure proper chemical reaction in the catalyst the fuel/air mixture must be kept at its stoichiometric ratio to within a degree of accuracy which is only possible by controlling the air-fuel ratio. The principles of exhaust gas cleaning systems with the Lambda-Sensor and in conjunction with the L-Jetronic and with carburetor engines were shown.

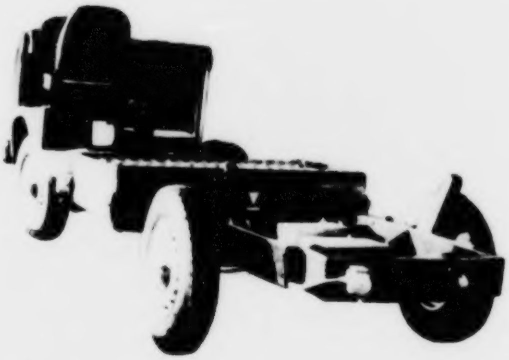
The increased severity of the exhaust gas regulations has also led to new developments in ignition systems. Up to now, power output and knock rate of the engine have been the determining factors for ignition timing but nowadays preservation of clean exhaust gases and fuel economy have also to be considered. As a result, the requirements on ignition voltage and spark energy (resistance to fouling, spark duration) i.e. on the reliability of mixture ignition are also increasing. Finally, vehicle manufacturers and operators expect that equipment manufacturers provide them with a system with easy maintenance or even with no maintenance at all.

To fulfil these requirements Bosch has developed a breakerless, maintenance-free electronic ignition system which went into regular production in 1974. A particular feature of this system is a rotationally-symmetrical actuator operating on the induction principle. This device is mounted in the distributor instead of the breaker. Resetting of the ignition point and the dwell angle at regular maintenance intervals is no longer necessary. It thus becomes possible to comply with legal requirements relating to exhaust gases over longer periods.

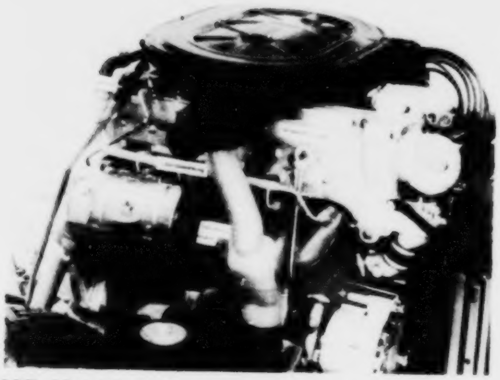
As possible alternatives to the internal combustion engine for particular applications Bosch has developed electric drive systems which are now ready for series production. A DC-motor and control system for light duty trucks and a control system for buses were shown in the exhibition. By using separately excited DC-motors with field weakening the advantages of the series motor can be combined with those of the shunt motor, i.e. high starting torque and nearly constant power over the whole range of operating conditions. The control systems are thyristor controls with regenerative braking. By the latter feature a gain of the operating range by about 30 % may be reached.

The technical data, such as acceleration, hill-climbing capability and the operating ranges now achievable, are quite adequate for urban traffic. Further requirements with respect to the operating range can be met by means of battery-changing technique or by hybrid solutions in which for example the electric drive system is supplemented by an internal combustion engine with clean exhaust gases. As a study, Bosch has developed a hybrid system. The principle was shown in a display chart. It embodies an internal combustion engine with a friction clutch and an attached electric motor. This system results in a great operating range in intercity traffic and, at the same time, in environmental protection in urban traffic.

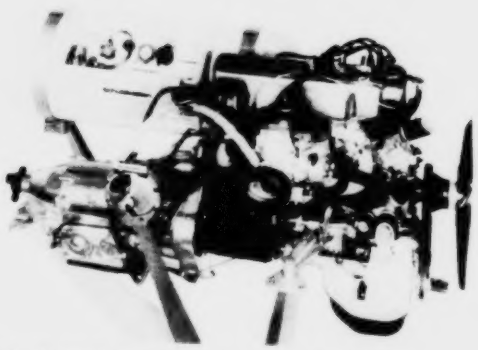
MB-O 305 with noise-insulated engine



MB-electro-transporter chassis LE 306

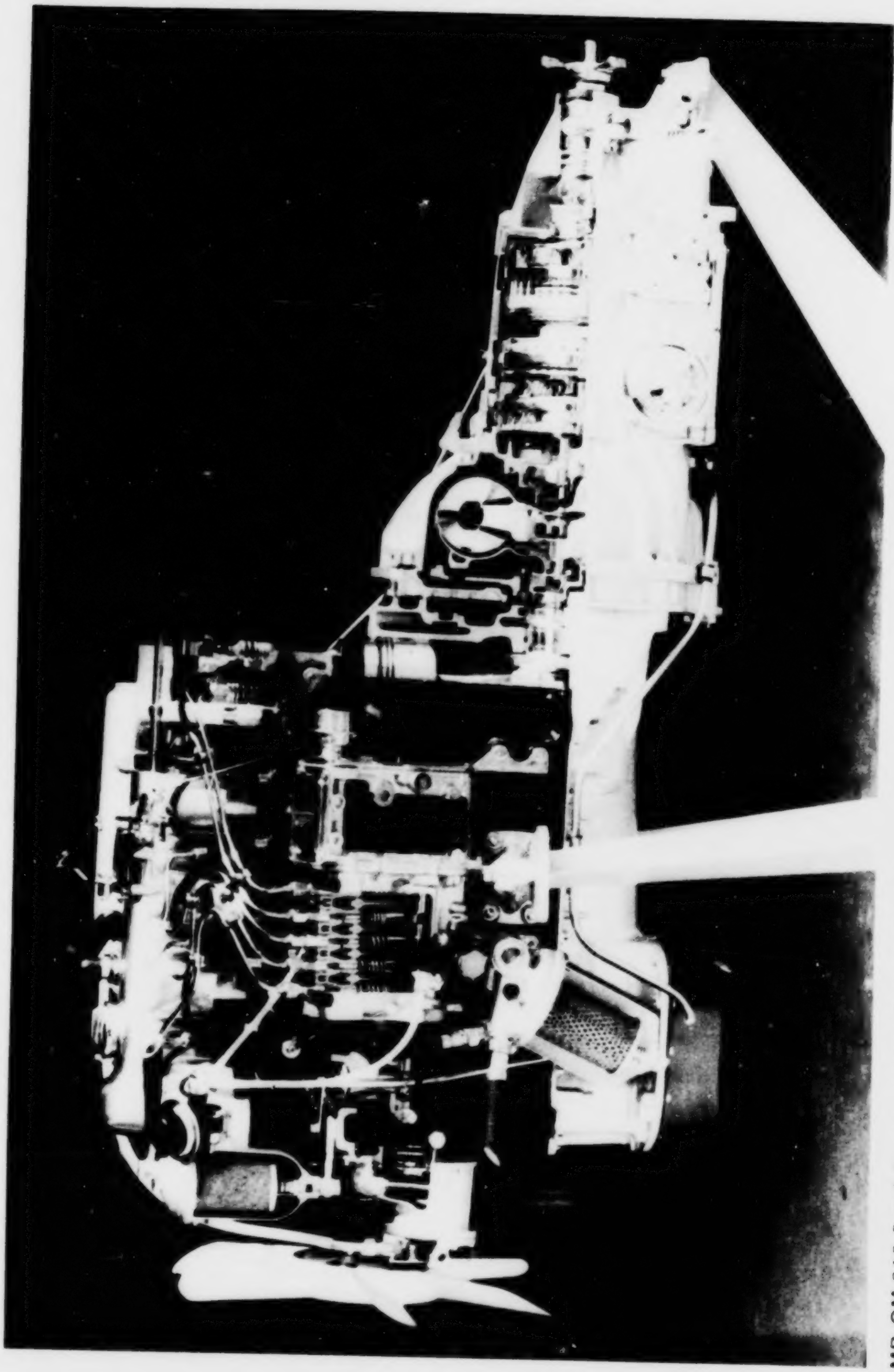


MB-M 110 with air injection and thermal reactor



MB-M 115, liquid gas operated

MB-450 SLC, methanol operated



MB-OM 616 5-cyl. low emission Diesel engine

On the exhibition, the DEUTSCHE VERGASER GESELLSCHAFT showed:

1. Schematic representation of the project plan of the RD-program of the DVG.
2. The multitude of configurations of intake manifolds used with a carburetter model are shown for 8 basic carburetter models and by the example of three cylinder heads with intake manifolds and carburetters.
3. Examples of exported 4-cylinder in-line production engines with designation of all auxiliary devices for cleaning the exhaust emissions for the model year 1975.

3.1 With downdraft compound carburetter, secondary air pump, and thermal reactor for USA including California.

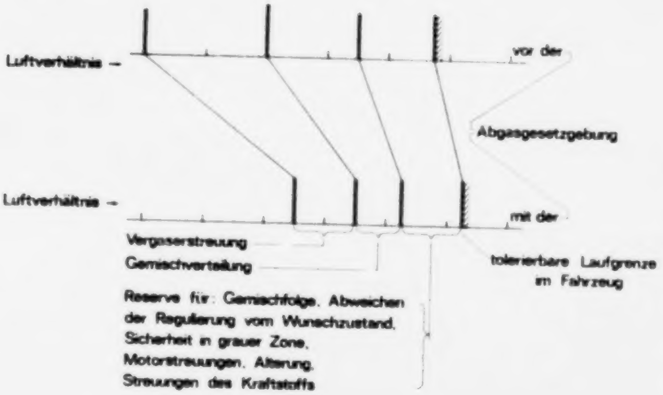
3.2 With constant pressure carburetter and secondary air pump for USA without California.

3.3 With downdraft compound carburetter, secondary air pump, and oxidation catalyzer for USA, including California.

4. Necessary elements to extend the design concept 3.3 to controlled admixture of secondary air in order to minimize the NO- and the CO/HC-emissions in one catalyzer bed at the same time.
5. Representation of an operation with feed-back controlled secondary air admixture in the CVS test by means of recording charts of the CO, HC, and NO concentrations as compared to an operation with oxidation only.
6. ZENITH injection with air volume measurement for a 6-cylinder engine. This is a continuous injection system with additional adaptability of the fuel metering to the engine characteristics as function of the intake manifold pressure by means of spatial cam control. The fuel is discharged by means of atomizer nozzles in front of the inlet valves of the cylinder.
7. Auxiliary emission control devices made by APG: Secondary air pump, secondary air valves for the various functions, EGR-valves, electric switch valves, and thermal switch valves.
8. Experimental model of a downdraft compound carburetter with additional stage to supply the pre-chambers of a stratified charge engine.
9. Illustratious and graphic representations of the DVG operations, e. g. figures 2 and 3.

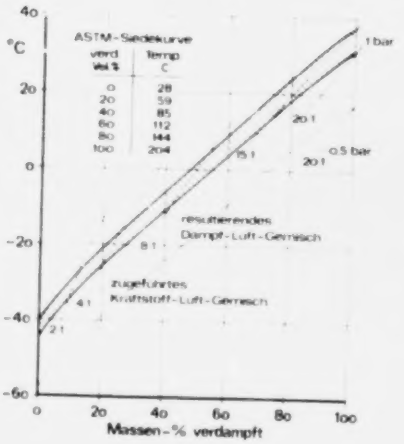
Figures:
1. DVG exhibition stand.
2. Diagrammatical representation. The origin of the variations of the equivalence ratio and the distance from the lean running limit.
3. Diagrammatical representation of the fuel part evaporated in the case of equilibrium as function of temperature, air-fuel ratio, and total pressure.

1


Luftverhältnis →
vor der
Abgasgesetzgebung
Luftverhältnis →
mit der
Vergaserstreuung
Gemischverteilung
tolerierbare Laufgrenze im Fahrzeug
Reserve für: Gemischfolge, Abweichen der Regulierung vom Wunschzustand, Sicherheit in grauer Zone, Motorstreuungen, Alterung, Streuungen des Kraftstoffs

ABMAGERUNGSKONZEPT SCHEMATISCH

2



ASTM-Siedekurve

verd Vol %	Temp C
0	28
20	59
40	85
60	112
80	144
100	204

GLEICHGEWICHTSTEMPERATUREN
NACH BRIDGEMAN, NBS 1934

3

Exhibits displayed by GES Gesellschaft für elektrischen Straßenverkehr mbH

GES Gesellschaft für elektrischen Straßenverkehr mbH, Düsseldorf, a subsidiary company of RWE AG, Germany's largest producer of electric power, is working on the solution of all problems concerning the battery-electric vehicle and its supply of power in close cooperation with the automobile, electronic and machine industry. Main motives for the founding of GES and its sister company SELAK (at a later stage to secure the supplying of electric energy to the electric car on the road) were the ever increasing environmental problems and the necessity to find a substitute for petroleum based derivates as energy for commercial traffic in well populated areas.

The following exhibits have been displayed by GES:

1.) Mercedes Benz Electro-Transporter (van)

power	27/56 kW
max. speed	75 km/h
payload	1000 kg

2.) VW-Electro-Transporter (van and pick-up)

power	16/32 kW
max. speed	75 km/h
payload	500 kg

3.) MAN-Electrobus SL-E

power	90/130 kW
max. speed	70 km/h
passenger capacity	100 persons

4.) MAN-Electrobus SL-E

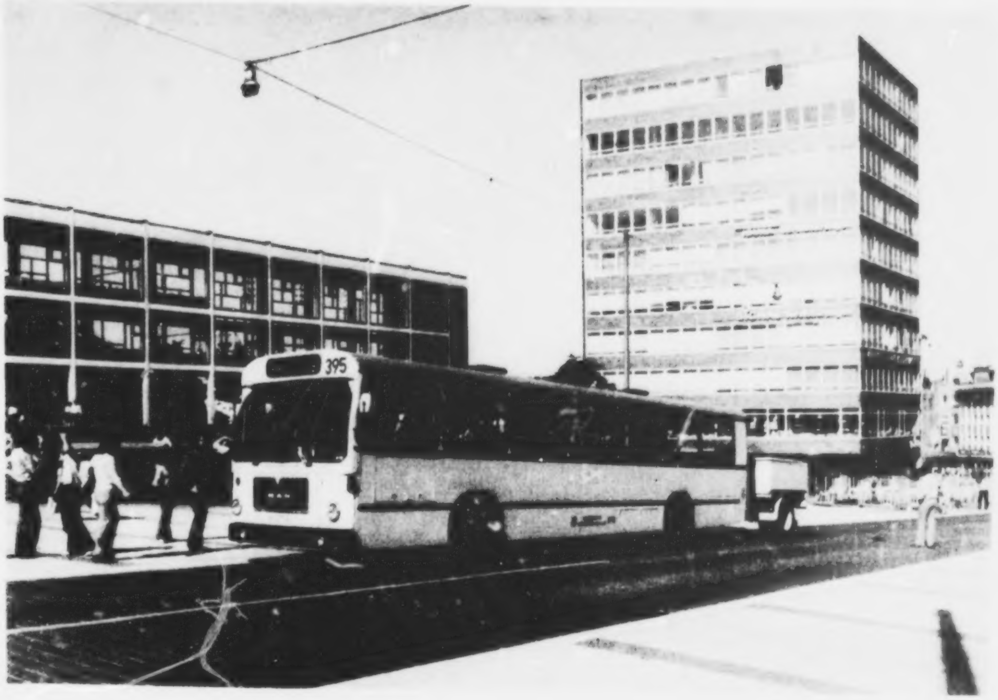
power	115/176 kW
max. speed	70 km/h
passenger capacity	100 persons

5.) Mercedes Benz Hybrid Bus

power	115/150 kW
max. speed	70 km/h
passenger capacity	100 persons

6.) MBB Electro-Transporter

power	22/44 kW
max. speed	80 km/h
payload	470 kg



Electrobus in the car-free pedestrian precinct of Mönchengladbach

Institut für Kraftfahrwesen, RWTH Aachen

Expositions:

1. Hybrid-drive with flywheel: complete drive-component with gear-shift, according to ill. no. 4.

2. Test vehicle with hybrid-drive, according to ill. no. 5.

This vehicle also served as demonstration car and furnished proof of the drive - component - capacity.

Development of the drive

The proof of function of the drive-concept has been given by the studies under review. They are followed by a prototype-phase, where the drive-components are being optimized separately and coherently.

With this, especially

- weight and construction volume will be reduced by means of block-system-drive,
- construction of flywheel meets safety-requirements in road-traffic
- the electrical component will be treated with a view to achieving a reduction of the input
- adaption of a low-consumption combustion-engine will be realized.

Object in View

1. Reduction of the energy requirement (fuel consumption) by means of direct, mechanical exchange of kinetic energy between vehicle and flywheel, i.e. by high energy-recuperation degree at intermittent performance.

2. Reduction of the energy requirement (fuel consumption) by means of improved mean drive efficiency of the combustion engine, by avoiding lower partial-load regions and idling in stand-still (dynamic performance tops are being overtaken by flywheel, therefore small dimensioning of the combustion engine).

3. Reduction of exhaust emission by means of smaller combustion engine of reduced consumption, and "desensitized" operation in advantageous ranges of family of characteristics.

Free of emission and of low noise level at purely electrical operation at reduced capacity over several kms, e.g. in city-range.

4. Specific weight not considerably less advantagerous than the one of conventional drives, i.e. decisively more advantageous than the one of f.e. battery-electrical-drives. (Advoiding great, installed performance of electrical components).

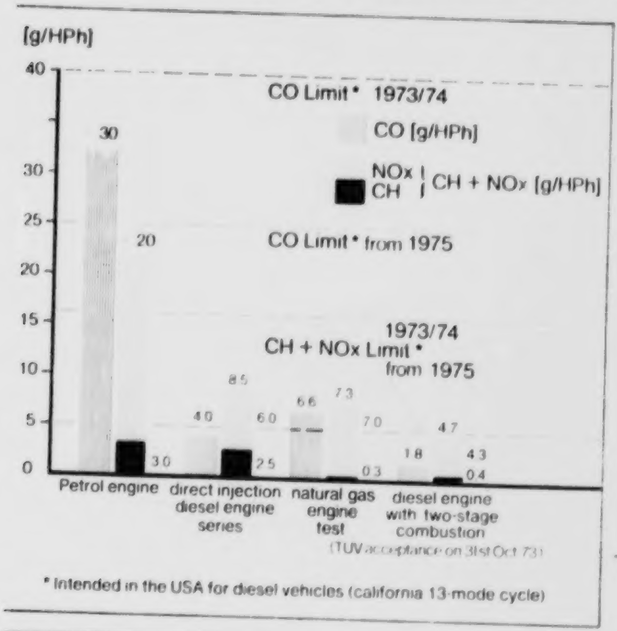
5. Factory costs not essentially higher than the ones of conventional drives, i.e. decisively lower than for battery-electrical-drives, by avoiding greater, installed performance of electrical components.

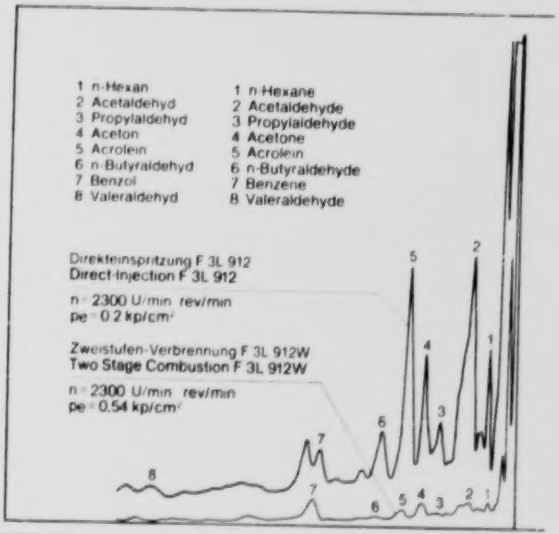
6. Total economy comparable to conventional drive, due to considerably reduced fuel-costs at only insignificantly higher factory costs, and barely deteriorated actual load factor (spezific weight).

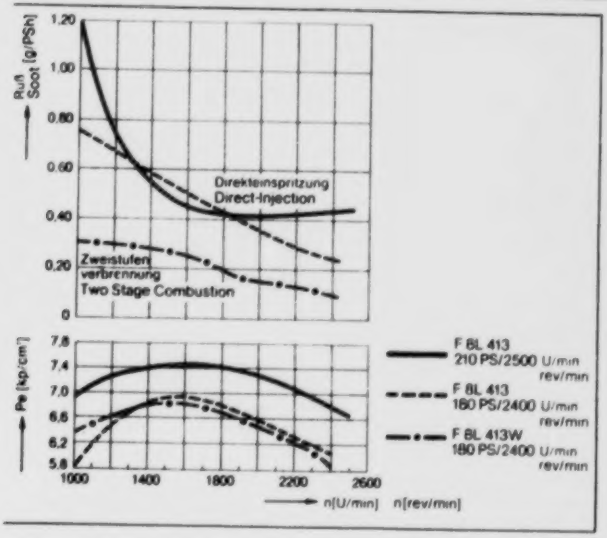
7. Driving capacities in range of short - distance-traffic at reduced constant tops speed at least equivalent to the ones of conventional drives. Operational range is the same as of conventional drives.

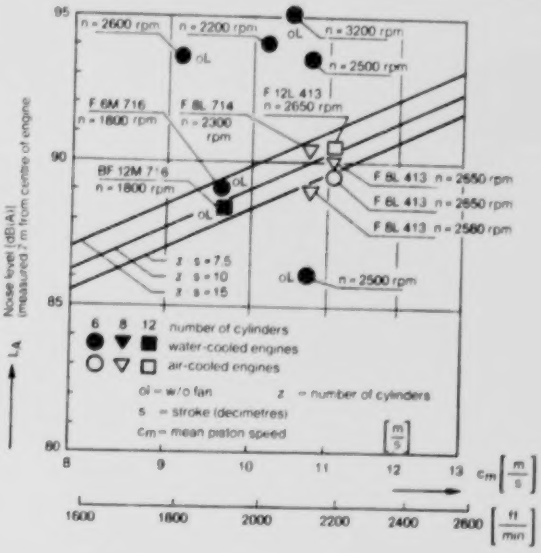
DEUTZ Low-emission Technology

Today's most economical automotive power unit with the most favourable exhaust-gas characteristics is the diesel engine. This solution requires no new fuels involving new distribution systems or completely new technologies and manufacturing facilities entailing a corresponding expenditure of political economy. Diesel engines with direct injection feature low fuel consumption coupled with high power-to-volume ratio.
Moreover, the DEUTZ two-stage combustion process permits fulfilment of the strictest exhaust-gas legislation - for example, the California limiting value for 1977 - since it exhibits a high-quality exhaust with little offensive odour. This was confirmed by a TÜV-acceptance test on 31st October, 1973.

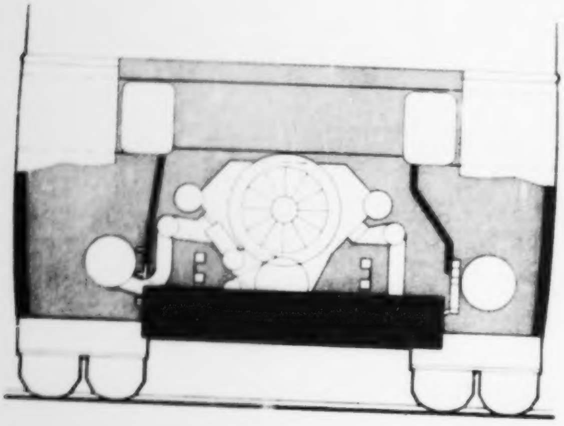


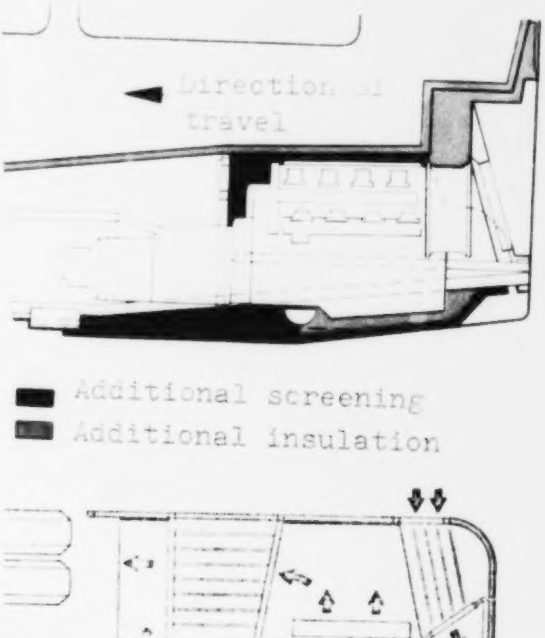




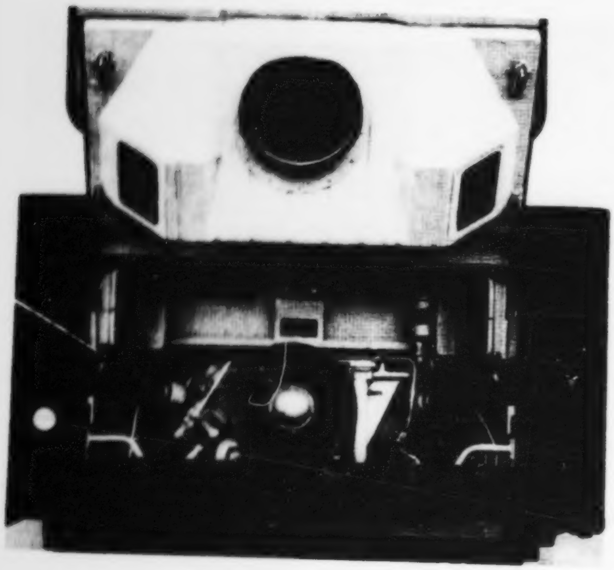


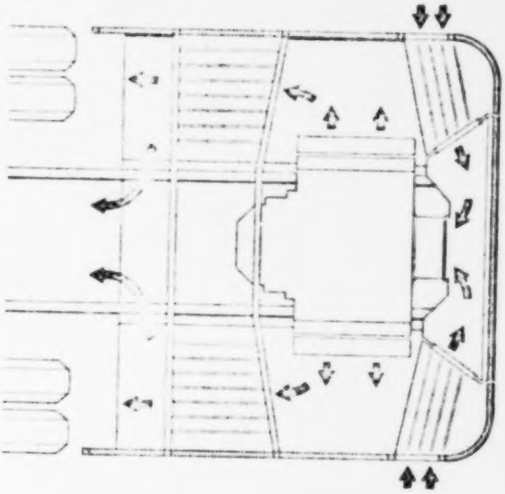
The modular construction principle employed in the case of DEUTZ air-cooled diesels permits an optimum choice of engines: Application of direct-injection engines where high engine power takes priority over the strictest regulations with regard to exhaust emissions. Employment of the same engines with two-stage combustion - whereby modifications are mainly confined to the pistons and cylinder heads - for those applications calling for a decidedly high degree of diesel exhaust quality (underground operation, enclosed spaces, built-up areas).
One practical example of such an environmental-conscious technology is demonstrated by the Magirus-Deutz city-line omnibus. It is particularly in local traffic (densely populated areas) that stricter regulations regarding exhaust and noise emissions will have to be fulfilled in future. By partial-enclosure of the low-emission DEUTZ diesel engine F8L 413W featuring two-stage combustion, and of the transmission components, it is possible to make this quiet engine even quieter without affecting its easy access.





■ Additional screening
▨ Additional insulation





M.A.N. Electro-bus

M.A.N. has been commissioned by GES to manufacture 22 battery-driven electro-buses for operation by the Mönchengladbach and Düsseldorf transport authorities. These buses have been based on the standard city service bus. In order to maintain the full passenger-carrying capacity, the 6 t lead batteries have been accommodated in a trailer. They allow an operational range of 8o km in normal service. Battery changing is fully automatic and can be carried out in less 5 minutes. Acceleration is similar to that of a Diesel bus and batteries can be recharged by means of regenerative braking, thereby extending the operating range.

The purpose is to obtain information on reliability, component life and actual operating costs under operational conditions.

Test Gas Turbine 6o22.712

Wide-ranging tests have been carried out with the test gas turbine 6o22.712 in M.A.N. trucks to study operational behaviour and to adapt transmissions.

Because of the development time available a heat exchanger was dispensed with at that juncture.

The results obtained are being used as a basis for a development programme currently being conducted on a special truck turbine with heat exchangers which reduce fuel consumption to about 2oo g/hph.

The turbine has for commercial vehicles the advantages of high power to weight ratio and cleanliness in operation. Development is now aimed at reducing fuel consumption and lowering manufacturing costs as well as at increasing the reliability and life of the individual components.

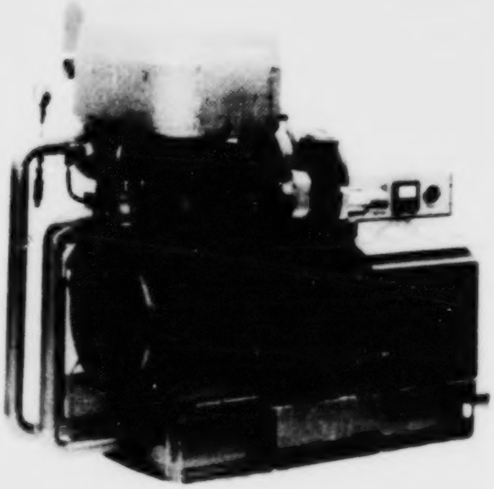
Multi-fuel engine

M.A.N. model L 92o4 FMV multi-fuel prototype engine, 7o BHP (DIN), M.A.N. "FM" combustion system. The use of a stratified-charge concept and direct injection enables this engine to burn a wide range of fuels with the good efficiencies of a direct-injection Diesel and with low emission levels. Aside from conventional hydrocarbon fuels ranging from Diesel oil to high-octane premium gasolines, the engine can also be operated on the lower alcohols such as methanol. This opens up the possibility in the case of any future changes in the fuel market to resort readily to available fuels without sacrificing economy.

Higspeed n/a truck Diesel engine

IH Diesel engine model DV 550, 220 BHP (DIN) with M.A.N.'s "M" combustion system. This production engine of the International Harvester Company in the United States, designed to power commercial vehicles, uses the "M" combustion system under licence from M.A.N. Careful matching of the process to the features of the IH design has enabled emission levels to be reduced considerably. Results of the CARB-13-cycle test have been around 5 g/HPh NOx puls emission.

Stirling Engine Generating Set



The Stirling engine has been jointly developed for six years now in the Federal Republic of Germany by M.A.N. and MWM. Their aim is to develop a Stirling engine which can be economically produced and runs reliably. Applications envisaged include commercial vehicles, power generating plants, boats and total energy systems.

The Stirling engine used in the generating set built by MWM (see illustration) has now progressed beyond the purely experimental stage. It already contains major assemblies newly developed by M.A.N. and MWM, such as the heater head and combustion system, which are suitable for later series production.

The generating set on display is driven by a one-cylinder Stirling engine with rhombic crankgear, model MAN-MWM 1-400/1, with a 20 kW output.

VW - RESEARCH FOR THE FUTURE

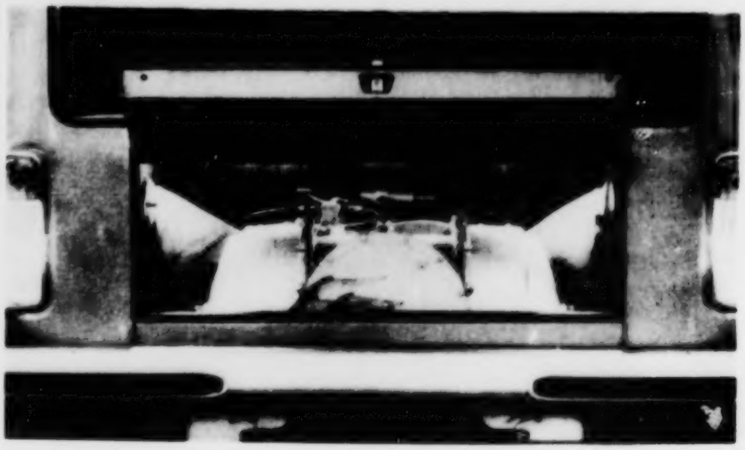
Methanol - fuel for tomorrow's cars ?

The fuel shortage situation showed us all too suddenly and clearly the extent to which we are dependent on gasoline obtained from crude oil. In addition, we now realise more clearly than ever before that the world's oil reserves are far from unlimited, and will in fact be exhausted within the foreseeable future. For these reasons, VW has been looking into the possibility of running cars with synthetic fuels. One promising alternative is the use of methanol.

VW Research has converted a number of standard production vehicles from gasoline to methanol operation including a VW Scirocco which has been presented at the exhibition. This carburator engine has been modified only at the inlet side (modified carburator, intensive heating of intake manifold by exhaust gases).

The VW experimental gas turbine VW-GT 70

A two-shaft gas turbine with regenerative air preheating and an integrated reduction gear. The power unit develops 55 kW. It can be installed complete with all auxiliaries in the unmodified engine compartment of various VW vehicles.



The gas turbine's operating principle: air is drawn in and compressed in a radial compressor stage.Next the compressed air is divided into two flows, each of which passes through the front section of a regenerator. Afterwars the flows are again combined and enter the combustion chamber through slots. Burning the fuel releases energy into this flow. This energy is extracted from the flow by the gasifier turbine to turn the compressor and by the power turbine to drive the vehicle itself.

The VW-GT 70 can be run on gasoline, diesel oil, paraffin, other petroleum distellates, or methanol.

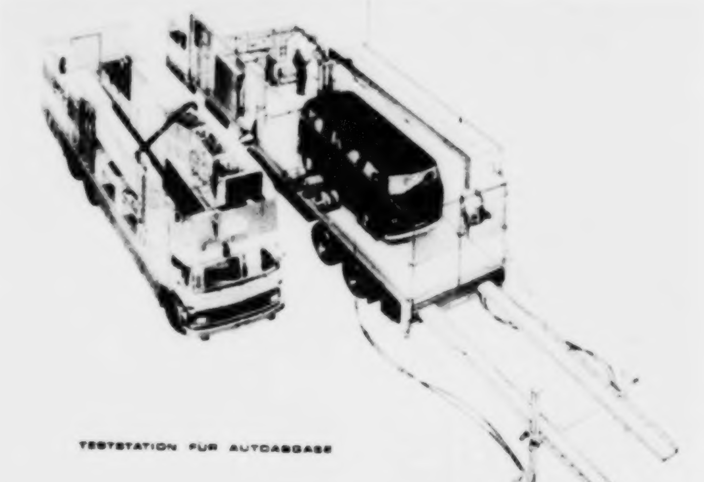
The VW stratified charge engine

The combustion chambers on the VW stratified charge engine consist of a main chamber and a pre-combustion chamber linked to it by a passage. During the engine's suction stroke, the entire combustion chamber is filled with a relatively lean mixture. Just before ignition a small quantity of additional fuel is injected into the pre-combustion chamber. VW develops air and water cooled stratified charge engines to reduce pollutant emissions at the best obtainable fuel econnomy.

The VW mobile test unit for automobile exhaust emissions

This unit is the first of its kind in Europe. It is employed for:

- correlation tests to other emission test laboratories;
- taking exhaust tests in field surveillance;
- obtaining emission tests on VW experimental vehicles under unusual circumstances (for instance at high altidudes during road testing in mountain areas).



Both vehicles are fully air conditioned and have their own power supply. The semi-trailer houses a chassis dynamometer, on which the vehicle under test is put through a simulated road driving program. The installed emission sampling systems work for every known test procedure.Inside the bus, an analytical laboratory has been set up, equipped with all the apparatus needed for measuring carbon monoxide, hydrocarbons, oxides of nitrogen, carbon dioxide and oxygen. A set of instruments for measurements of immission is also available. The laboratory even features its own computer. The sensitive analytical equipment is calibrated by calibration gases, carried along in steel cylinders.

SESSION 2

Reduction of Exhaust Emissions for Conventional Internal Combustion Engines Considering Fuel Economy Improvements

2ème SESSION

Réduction des gaz d'échappement des moteurs conventionnels à combustion interne compte tenu d'une meilleure économie de combustible

THEMENGRUPPE 2

Maßnahmen zur Verringerung der Schadstoffemissionen bei der Weiterentwicklung von konventionellen Kraftfahrzeugmotoren unter Berücksichtigung der Kraftstoffausnutzung

77

A Study of Technological Improvements in Motor Vehicle Fuel Consumption.

Donald A. Hurter
Arthur D. Little, Inc.
Acorn Park
Cambridge, Mass. 02140
U.S.A.

A study was conducted to determine potential improvements in automobile fuel consumption based on innovative design. Standard- and compact-size reference vehicles were selected. Obvious technological innovations that would save on fuel consumption were identified and evaluated. Operation of reference vehicles equipped with innovative components was computer-simulated to predict fuel usage and vehicle performance. Total systems evaluation of each vehicle was determined for technical compatibility, compliance with constraints, user acceptability, and manufacturer adaptability.

The Transportation Systems Center, U.S. Department of Transportation (DOT), and the U.S. Environmental Protection Agency (EPA) contracted with Arthur D. Little, Inc. (ADL), to conduct a study of technological improvements in motor vehicle fuel consumption.

PURPOSE

The primary objective of the work was twofold: (1) to provide some insight into the factors which affect fuel consumption in the passenger automobile, and (2) to identify and evaluate the individual technological improvements which will be available in the near term for possible incorporation into a vehicle design which will reduce the fuel consumption (gallons per mile) level of the 1973 passenger automobile by 30%, or improve its fuel economy, measured in miles per gallon (mpg), by 43%.

SCOPE

This six-month study involved the following tasks:

Task 1 – Consisted of *selecting reference vehicles* for evaluating the improvements. These vehicles were to be 1973 standard size (3,800 to 4,500 lb) and compact size (2,750 to 3,400 lb) cars.

Task 2 – Consisted of an *examination of the manner in which fuel consumption tests were specified* and run so that data and information could be obtained, compared, and evaluated on a common basis for each improvement.

Task 3 – Consisted of *compiling well documented experimental data* that could be used to substantiate how the power is used in operating an automobile and also data that could be used to identify and evaluate possible improvements.

Task 4 – Consisted of *analyzing where power is used in operating an automobile* as a means of determining what areas should receive the greatest priority in identifying and evaluating possible improvements and subsequent fuel savings.

Task 5 – Consisted of utilizing the information and test results obtained *for computer modelling and simulation of fuel economy and performance levels for both sizes of vehicles* – standard and compact – to assess the relative degree of improvement possible for each device, and to provide indications of how the improvements might be combined into a synthesized vehicle design.

Task 6 – Consisted of *combining the most promising improvements*, based on automotive engineering judgment, into a complete synthesized design vehicle, and of simulating the fuel economy improvement and performance of the vehicle by means of computer modelling.

Task 7 – Consisted of *a ranking of these designs* – having ascertained what the relative improvements would be for each synthesized design – based on compliance with the general acceptance criteria.

STUDY CONSTRAINTS

Each technical improvement should be in a mature state of development or have reached an off-the-shelf hardware stage, and should contribute significantly to a 30% reduction in fuel consumption (gal/mile) or 43% improvement in mpg when combined into the optimized vehicle design.

The synthesized, optimized vehicle should be capable of being mass-produced by 1980.

The performance and transient response of the optimized vehicle design should not be significantly different from the reference vehicle for each of the two sizes – standard and compact.

Improvements which result in deviations from the federal standard for safety, emissions, and noise should be identified and, perhaps, not incorporated in the vehicle design.

The emission standard used for this study an the 1977 standards, as follows:

HC	0.41g/mile
CO	3.4g/mile
NO_x	2.0g/mile

The following factors affecting user acceptability should be considered and carefully evaluated when compared with the composite reference vehicle (Table 1):

- Cost; initial operating cost and repair and maintenance costs to provide a discounted life cycle cost,
- Operating conditions; such as comfort, handling, and driveability,
- Appearance,
- Passenger and luggage capacity,
- Reliability, durability, and ease of maintenance and repair.

TABLE 1 1973 COMPOSITE REFERENCE VEHICLES

Passenger Vehicle	Standard Size	Compact Size
Body style	2-door hardtop	4-door sedan
Standard equipment	Automatic transmission, power steering, air conditioning	Automatic transmission, power steering, no air conditioning
Curb weight	3,900 to 4,500 lb.	2,860 to 3,400 lb.
Wheel base	120" to 122"	108" to 111"
Number of cylinders	V-8, 350 to 400 C.I.D.	6 in line; 225 to 250 C.I.D.
Rated horsepower	145 to 200 HP @ 3,800 to 4,000 RPM	88 to 105 HP @ 3,200 to 4,000 RPM
American Motors	Ambassador	Hornet
Chrysler	Fury	Valiant
Ford	L.T.D.	Maverick
General Motors	Impala	Nova

APPROACH

Our approach to the study was as follows:

First, we characterized the reference vehicles (see Table 1). Then we compiled reference vehicle fuel usage and performance data from manufacturers. We identified improvements and obtained pertinent data. We verified there improvements through contact with manufacturers and evaluation of their test and performance data. We then simulated vehicle performance through computer modelling. Finally, we made a technical analysis of the potential of the devices considered, combined the best individual improvements into optimized vehicle designs, and evaluated each synthesized vehicle design.

Many feasible improvements were examined. Those which did not meet the conditions of the study were discarded. Those which remained were combined, as appropriate, for each class of vehicles. The result was 16 vehicle designs, for each of which we evaluated the projected fuel economy gains and fuel breakeven costs per gallon.

FINDINGS

Individual technical innovations may improve fuel economy (MPG) by: reducing the weight of the body/chassis, reducing the drag of the body, improving the engine-to-transmissions load matching, and improving engine efficiency. Table 2 shows the percent of improvement for each of the selected improvements and the breakeven cost per gallon of fuel which when multiplied by the fuel saved will just pay for the additional incremental and operating costs.

Table 3 shows the various improvements combined in a logical fashion for each class of vehicle, resulting in 16 vehicle designs.

Table 4 shows the fuel economy gains and full break-even cost per gallon for the various synthesized vehicles.

Figure 1 shows the relative contribution for each improvement as a part of the total improvement.

Generally, it can be shown the combination of improvements in the body and tires amounts to 10%. Engine-transmission matching improvement amounts to approximately 12-18%, regardless of the type of power plant used.

Summary of Fuel Economy Gains and Costs for Synthesized Vehicle Designs (See Table 5)

The lean-burn concept results in the lowest total incremental cost to the first owner and for the life cycle of the vehicle for both the compact and the standard size car. Furthermore, it is the most cost-effective solution with either a four-speed automatic transmission with lockup or a continuously variable transmission. This concept becomes cost-effective when the fuel cost reaches approximately $0.24 to $0.41 per gallon for both sizes of automobiles.

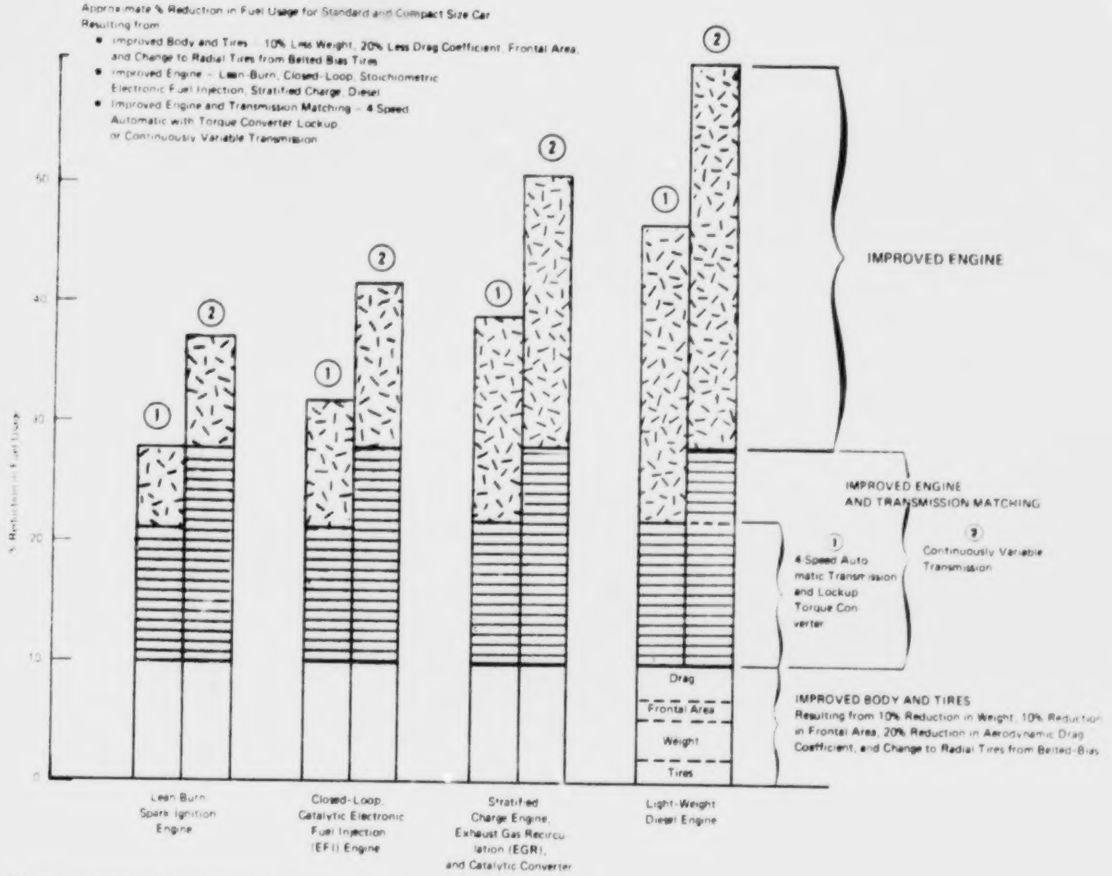
TABLE 2 GROUPING OF INDIVIDUAL IMPROVEMENTS

	mpg Improvement (%)	Fuel Cost per Gallon to Break Even in 10 Years, 100,000 miles ($)
Improved Body and Chassis		
• Reduce frontal area by 10%	1.3	–
• Reduce weight by 10%	3.	0.52
• Lower drag coefficient by 20%	3.	–
• Reduce rolling resistance – radial tires	3.	0.15
• Combination of above	10.	0.17
Improved Engine and Transmission Matching		
• Four-speed automatic with torque converter lock-up	12	0.10
• Continuously variable transmission	22	0.16
Improved Engine Systems		
• Homogeneous spark ignition		
– Lean burn concept	7.5	0.56
– Stoichiometric air/fuel ratio using closed-loop, self turning systems and catalytic converters	10	1.30
• Heterogeneous spark ignition		
– Open-chamber stratified charge	18	0.83
• Heterogeneous compression ignition		
– Pre-chamber light-weight diesel	22	0.50

TABLE 3 LIST OF 16 SYNTHESIZED VEHICLE DESIGNS

Engine Concept Type	Transmission Type Matched to Engine	Standard Size Vehicle	Compact Size Vehicle	Total Vehicles
Lean Burn (L.B.)	• 4 Speed Automatic with Torque Converter Lock up (4 S.A.T.C.L.U.)	x	x	2
	or			
	• Continuously Variable Transmission (C.V.T.)	x	x	2
Closed Looped Exhaust Emission Control System (C.L.E.E.C.S.)	• 4 S A T C L U	x	x	2
	or			
	• C V T	x	x	2
Stratified Charge (S.C.)	• 4 S A T C L U	x	x	2
	or			
	• C V T	x	x	2
Lightweight Diesel (L.W.D.)	• 4 S A T C L U	x	x	2
	or			
	• C V T	x	x	2
4 Engines	2 Transmissions for Each Engine Type	8 Systems	8 Systems	16

Note: All vehicle designs based on using radial tires 10% reduction in weight, (frontal area) and 20% reduction in aerodynamic drag coefficient



① Synthesized vehicle with 4-speed automatic transmission and torque converter lock-up

② Synthesized vehicle with continuously variable transmission

FIGURE 1 REDUCTION IN FUEL USAGE FROM PROPOSED IMPROVEMENTS

TABLE 4 PERCENT FUEL ECONOMY GAINS AND FUEL BREAK-EVEN COSTS/GALLON – SYNTHESIZED VEHICLES*

Engine Concept	Modified Automatic Transmission	Continuously Variable Transmission
Lean Burn Gain	28%	37%
Break-even cost/gallon	$0.27	$0.25
Stoichiometric Gain (closed-loop control)	32%	42%
Break-even cost/gallon	$0.53	$0.46
Stratified Charge Gain	39%	51%
Break-even cost/gallon	$0.48	$0.42
Diesel Gain	47%	60%
Break-even cost/gallon	$0.32	$0.30

*All vehicles have light-weight, improved body construction and radial tires.

The closed-loop exhaust emission control system, either with four-speed automatic transmission and lock-up or continuously variable transmission, has a very high total incremental cost for either the 3- or 10-year period. It has a fuel cost per gallon breakeven point almost double that of the lean-burn concept, ranging from $0.68 (3 years) to $0.59 (10 years) per gallon for the compact car and $0.63 (3 years) to $0.44 (10 years) per gallon for the standard car.

The stratified charge engine concept, either with the four-speed transmission or the continuously variable transmission, has the highest total incremental cost over the reference vehicles of all four concepts and requires a fuel cost per gallon to break even of $0.63 (3 years) to $0.43 (10 years) for the compact car and $0.74 (3 years) to $0.41 (10 years) for the standard car.

The light-weight diesel has a relatively high incremental total cost, but it begins to approach the cost effectiveness of the lean-burn concept for the 10-year, 100,000-mile life cycle. The breakeven fuel cost under these conditions is $0.33 per gallon for the four-speed transmission and $0.29 per gallon for the continuously variable transmission. For the 3-year period, the cost effectiveness is not so attractive, resulting in a fuel cost per gallon ranging from $0.62 per gallon to $0.55 per gallon, depending upon the transmission.

CONCLUSIONS

Given the constraints of our study, the goal of a 43% improvement in fuel economy (mpg), or 30% reduction in fuel usage (gpm), for the compact and standard sizes of vehicle appears attainable by the early 1980's. All individual innovations yielding substantial gains in fuel economy without changing the performance of either size of car or driver habits may be grouped into one of three major technological areas:

- Changes in vehicle structure which reduce weight, aerodynamic drag, and rolling resistance;

- Improved matching of the engine coupling to the road load by use of a modified transmission now in use, or continuously variable transmission presently being developed; or
- Near-term (mid-1970's) improvement in present engine operating efficiency or substitution of conventional gasoline engines by the diesel or stratified charge-type engines for the long-term 1980's.

However, maximum gains can be made if the individual innovations are combined using a total systems approach, therefore, based on our findings we conclude that the lean-burn concept would be the most cost-effective system to develop for the 1977 to 1980 period. For the 1980 to 1985 period, the light-weight diesel would be the most cost-effective design. The closed-loop exhaust emission control system and the stratified charge systems would be the least attractive to develop.

FACTORS TO CONSIDER IN INTRODUCING TECHNOLOGICAL IMPROVEMENTS

Technological Risks — These risks range from:

- Low — for weight, drag, rolling resistance reduction, and improved automatic transmission, to
- Medium — for developing lean-burn and diesel engines, to
- High — for closed-loop exhaust emission-controlled catalytic converter engines, stratified charge engines, and continuously variable transmissions because of required durability and higher maintenance costs.

Lead Time

Lead time for introducing improvements does not follow the degree of risk necessarily, e.g.,:

- Near Term — Lightened body, chassis, tires, and present automatic transmission (next major body style change, 1977-1979); lean-burn and closed-loop approach (1977-1980);
- Long Term — Stratified charge, diesel, and continuously variable transmission (1981-1984).

Customer Acceptance —

Customer acceptance would depend on the degree of development and cost of fuel at the time of introduction, since there could be some sacrifice in driveability, durability, and repair/maintenance costs. We rank the improvements as follows:

- *High Acceptance* — Less weight and drag, improvement of present-type automatic transmission and radial tires; diesel engine, if odor problem is solved.
- *Medium Acceptance* — Continuously variable transmission, because of possible engine lugging; lean burn, because of poor driveability and possible need for high octane fuels to permit the raising of compression ratios.
- *Low Acceptance* — Closed-loop exhaust emission control, because of durability and replacement costs of catalytic converter and high initial cost with low fuel economy gains; stratified charge, because of high initial cost, possible poor driveability response and high maintenance cost, particularly if catalytic converters are required.

TABLE 5 SUMMARY OF POTENTIAL IMPROVEMENTS IN COMPACT AND STANDARD SIZE VEHICLES

VEHICLE CONCEPT	STANDARD SIZE							REMARKS	COMPACT SIZE			
	% FUEL ECONOMY IMPROVEMENT	% FUEL USAGE REDUCTION	ESTIMATED FUEL SAVED IN 10 YEARS AND 100,000 MILES	ESTIMATED NET SAVINGS BASED ON 10 YEARS @ [illegible]/GAL	RISK	TIME FRAME	COMPLIANCE WITH CONSTRAINTS		% FUEL ECONOMY IMPROVEMENT	% FUEL USAGE REDUCTION	ESTIMATED FUEL SAVED IN 10 YEARS 100,000 MILES	ESTIMATED NET SAVINGS BASED ON 10 YEARS @ [illegible]/GAL
1. Lean Burn Engine and Thermal Reactor. Light Weight Vehicle with Radial Tires and Either 4 Speed Automatic and Torque Converter Lockup Transmission or Continuously Variable Transmission	24 34	20 28	1376 1836	862 974	Low High	1978-1981 1981-1984	Does not meet interim 1976 standards As yet (see Appendix Ethyl Data 3/28/74) Loaded Engine may present problem with NO_x	• Many Lean Burn Concepts Being Developed • Readily Adaptable to Present Engines • Driveability may be a Problem Due to Cylinder to Cylinder and Cycle to Cycle Variation • Combination of New Engine and C.V.T. Presents High Risk • Does not Require Catalyst, but may Require High Octane Fuel or Leaded Fuel for Best Economy • Partial Solution	31 41	25 32	1302 1666	611 800
2. Engine Equipped with Closed Loop Stoichiometric Fuel Control and Catalytic Emission Control. Light Weight Vehicle with Radial Tires 4 Speed Automatic and Torque Converter Lockup Transmission or Continuously Variable Transmission	29 39	26 34	1780 2338	432 717	Low Except for Durability of Catalyst Medium High	1975-1977 1981-1984 1981-1984	Emission Control Dependent on Keeping in Tune and Life and Reliability of Catalyst	• Start Development Based on Proposed 1975 Engines with Optimized Spark Timing, Improved Carburetor, and Catalytic Converters. Improve with Closed Loop if System is Successful • Catalytic Muffler Unproven in Public Hands • Uses Noble Metals which must be Imported • Catalyst may have to be Replaced at 50,000 Miles • Requires Development of Durable & Reliable O_2 Sensor	35 45	29 37	1610 1826	272 482
3. Stratified Charge Engine (May Require Catalysts for HC) Light Weight Vehicle with Radial Tires 4 Speed Automatic and Torque Converter Lockup or Continuously Variable Transmission	38 51	30 39	2084 2682	538 1000	High Very High	1982-1984 1982-1984	Good Results to Date	• Engine must be Developed into Reliable Power Plant • Requires Both Fuel Injection System and Spark Ignition System • Maintenance Cost Probably High • Concept Being Explored Extensively and Answers Should be Available in Near Term • Highest Risk of All Concepts because of variable displacement Injection System and Ignition System Durability • Uncertain Cost Effectiveness • Durability of Catalysts a Problem	42 52	35 42	1822 2188	501 680
4. Prechamber Diesel Engine Light Weight Vehicle with Radial Tires 4 Speed Automatic Transmission and Torque Converter Lockup or Continuously Variable Transmission	44 60	36 46	2476 3164	1046 1462	Medium High	1982-1984 1982-1984	HC & NO_x May Present Problem with CVT	• Good Cost Effective Solution • Technical Risks, Medium to High Development Required on Odor, Cold Start, and Weight • Should be Reliable with Low Maintenance • Changeover to Large Scale Diesel, Fuel Production must be Studied	50 60	40 47	2084 2448	888 1088

* Figures in this chart, to the best of our knowledge, include the effects of emission controls. We feel that the improvement concepts included in this table should meet the 1975 federal emission regulations, will probably meet the interim 1976 federal emission regulations, but will not meet the original 1976 regulations. Actually, we feel that building and testing the proposed vehicle models is the only way to validate the overall emission/fuel consumption outputs.

All Vehicles must be Engineered to Meet Safety Requirements.

Preliminary Findings on Truck Fuel Economy Study

Following the study of automotive fuel consumption improvements, ADL began a similar investigation into fuel economy improvements for trucks.

Our preliminary analysis of available data indicates that fuel economy improvements on an individual vehicle basis would range from 20 to 30% depending on the vehicle's gross weight, its purpose and its typical trip length.

The analysis indicated the most significant payoff options to be:

- Increased substitution of diesel engine for gasoline engine
- Optimized cooling system with variable-speed fan drives
- Use of radial tires or wide-base singles
- Derating of engine power and speed

No environmental degradation could be identified with these technical improvements. Noise reduction would result from the cooling system improvements but would be offset somewhat by expanded diesel engine use.

The major technological shortcomings lie in the realm of viable and equitable fuel economy measurement techniques for heavy duty vehicles. At the present time, there are no accepted sets of driving modes for either road tests or dynamometer tests.

High priority needs to be given to the development of fuel economy measurement techniques, and final measurement should reflect truck productivity in ton-miles per gallon of fuel.

Reduction of air pollution by internal modifications of a spark ignition engine

Prof. Dr. Ing. E.W. HUBER
Dr. K.H. PRESCHER
Institut für Motorenbau Prof. Huber e.V.
D-8000 München 81
Eggenfeldener Straße 104

Optimisation of the internal factors of the engine facilitates a marked reduction of polluting emissions.Ignition parameters and operation with excess air are of great influence. Shape of combustion chamber and compression ratio are also important.The influence of different mixture formation devices is low in stationary operation. Adjustment of valve timing facilitates a reduction of NO-emission. Combination of the individual measures gives reductions of more than 50%.

L'optimisation des facteurs internes du moteur permet une réduction sensible de l'émission d'éléments polluants. Les paramètres d'allumage et le fonctionnement avec excès d'air ont une influence considérable. La chambre de combustion et le taux de compression sont également importants.En marche stationnaire, l'influence des différents dispositifs de formation du mélange est faible. Un réglage des temps de commande des soupapes se traduit également par une diminution de l'émission de monoxyde de nitrogène (NO). On peut obtenir une réduction des émissions de plus de 50% en combinant différentes mesures particulières.

Die Optimierung motorinterner Einflußgrößen läßt eine deutliche Reduzierung der Schadstoffemission zu.Großen Einfluß haben die zündungsseitigen Parameter und der Betrieb mit Luftüberschuß. Bedeutung haben ebenfalls die Brennraumform und das Verdichtungsverhältnis.Der Einfluß verschiedener Gemischbildungsanlagen ist bei stationärem Betrieb gering.Geänderte Steuerzeiten lassen eine Verminderung der NO-Emission zu. Durch Überlagerung der Einzelmaßnahmen können Verminderungen um mehr als 50% erreicht werden.

A considerable part of air pollution in large cities today is caused by motor vehicles operating with spark ignition engines. It is therefore necessary to reduce the noxious products of combustion to limits, which are acceptable from a medical and ecological standpoint, and at the same time keep the production and running cost of the vehicle at an economic level. To this end attempts to control the pollution at its source, in the engine cylinder, should be first made.

The following parameters were investigated:

- the shape of combustion chamber (which influences the mixture movement created within the combustion chamber and varies surface/volume ratio)
- the ignition timing
- the spark energy
- the gap between the electrodes of the spark plug
- the duration of the spark
- the compression ratio
- the different methods of mixture formation
- the variation of valve timing

A prominent influence on combustion and emissions is the shape of the combustion chamber. The influence on combustion and emissions by variing the combustion chamber geometry was achieved by the use of different piston shapes and one cylinder head. The piston geometries investigated are shown in figure 1.

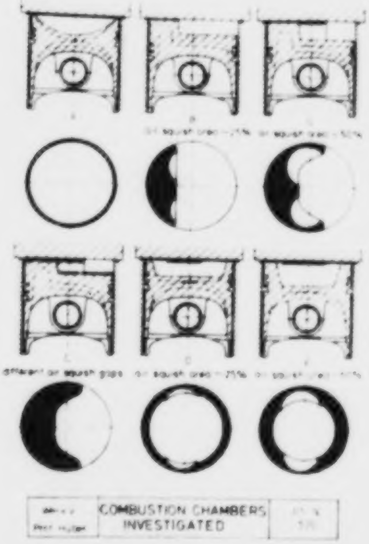


figure 1

Shape A is a hemispherical chamber with no squish area and a favourable surface to volume ratio. Shape B and C use a step-shaped piston with squish areas of 25% and 50% respectively. The shape C was further investigated with regard to a variation in the squish gap. Shapes D and E are of the bowl in piston type with squish areas of 25% and 50% respectively. A critical evaluation of the different shapes examined under the same operating conditions showed significant trends.

The brake specific fuel consumption as a function of equivalent air/fuel ratio λ (see footnote) at low load (engine speed 2000 rpm, b.m.e.p. = 3 bar, ignition timing 20° BTDC) shows, as expected, that there is no marked difference in fuel consumption, see figure 2. Shape D has the highest fuel consumption, while shape C (1 mm squish gap) gives the optimum.

However, if hydrocarbon emissions are compared, the stepped pistons (B and C) have the highest emission value, while the bowl-type chambers D and E show the best results, see figure 3. The hemispherical chamber A is near the optimum. The top ring lands of the stepped piston shapes are necessarily larger than those of the other piston shapes, so that this influence will also be found, when considering the stepped piston geometry.

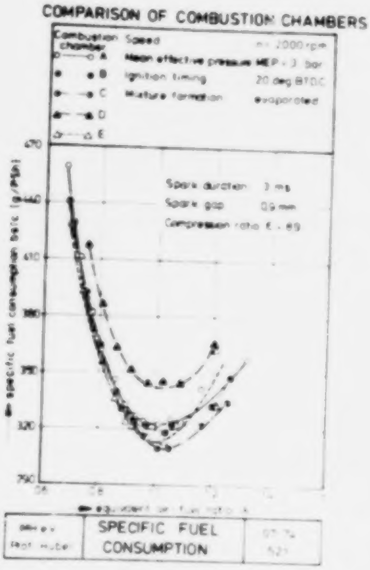


figure 2

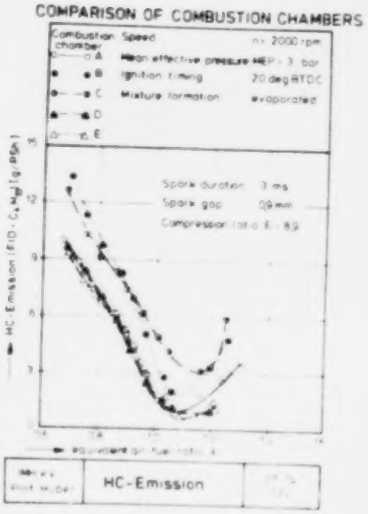


figure 3

A similar effect is to be found, if the concentration of nitric-oxides (NO), figure 4, is considered. As with hydrocarbons, shapes B and C give the highest concentrations, followed by those produced by shapes A and E, while shape D produces the lowest concentrations. Lower NO concentration coincides with higher specific fuel

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✱: The equivalent air/fuel ratio λ is defined as the quotient out of the actual air/fuel ratio and the stoichiometric air/fuel ratio consumption, which is evidently caused by a slower combustion process and lower peak temperatures. The CO emission was practically independant of the shape of combustion chamber.

If the different combustion chamber shapes are compared at a higher speed and load (3000 rpm and b.m.e.p. = 6 bar), it can be seen that the trends are the same but the influence of combustion chamber geometry is less. It is clear that squish areas can be benefitial to fuel economy and emission levels. Position of the squish areas relative to the position of the spark plug has a decisive influence, which can be seen by comparing shapes B and C with D and E. In combination with the systematic examination of the different chamber shapes the influence of the top ring land was explored. It was found that the top ring land and the squish gap have a great influence on hydrocarbon emissions. Figure 5 shows emission values with two different top ring lands,the squish gap being constant. Later experiments with a further reduction of top ring land to 5 mm extended this trend.

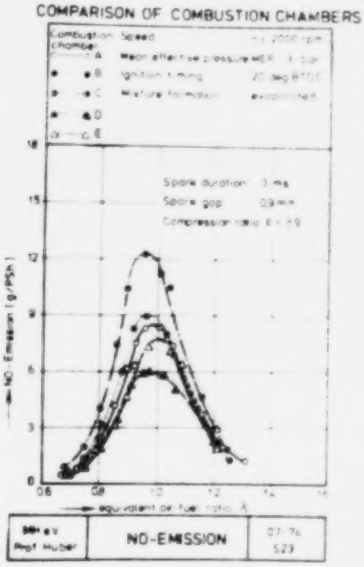

figure 4

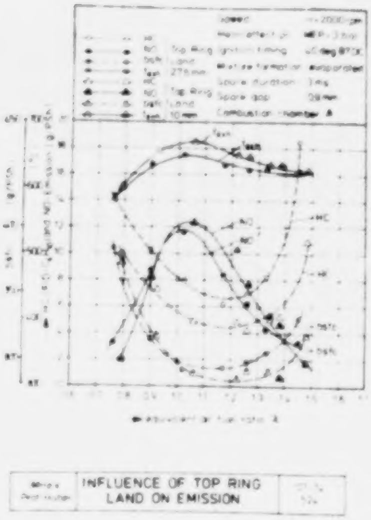

figure 5

The only parameter that leads to reduction of both hydrocarbons and oxides of nitrogen is a reduction of ignition advance. Figure 6 and 7 show a pronounced reduction of both components. This reduction of emissions, however, is accompanied by a severe loss in fuel economy, see figure 8, especially at very late ignition timing. Therefore, this way of reducing emissions will only be practicable at part load.

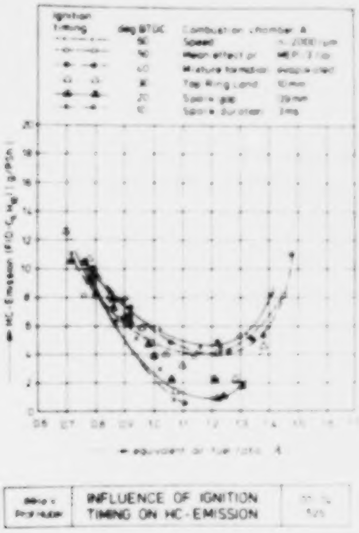

figure 6

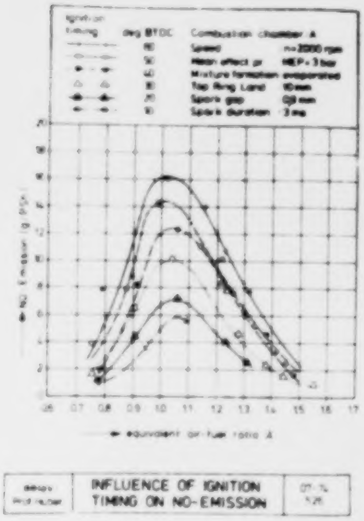

figure 7

Other ignition parameters lead to better ignition of lean mixtures. Ignition systems with different spark energies were used, and the influence of the spark gap was also investigated. Operating the engine without a carburettor but feeding a premixed fuel vapour/ air mixture to the cylinder with large spark gaps and long spark duration extended the lean operation limit combined with slight improvements in brake specific fuel consumption and hydrocarbon emissions. It was found that ignition systems providing high spark energies did not extend the range of operations. It is not clear, whether failure of initial ignition or a low combustion speed is the reason for this.

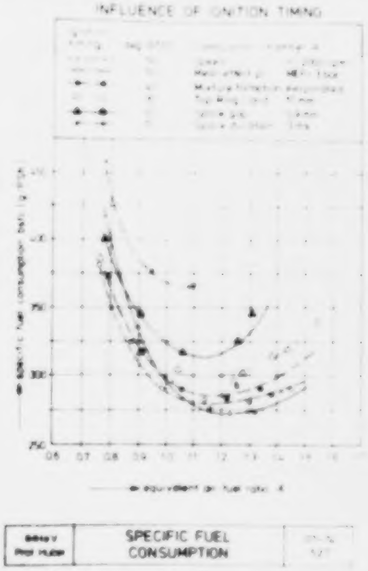

figure 8

All efforts to extend the lean limit of operation have to attempt to increase the speed of flame propagation. These include the thermodynamic conditions of the load (gas temperature and pressure), the mixture motion, the spark plug geometry, its location in the combustion chamber and its operating conditions. Investigations concerning these factors have been initiated in our Institute

An influence on emissions in spark ignition engines frequently discussed is that of compression ratio. Investigations were undertaken with compression ratio of 8.9 and 7.4, using the same high octane fuel as in the tests described above. In this way the influence of different fuels was eliminated. Low octane fuels, especially those free of lead, were not considered.

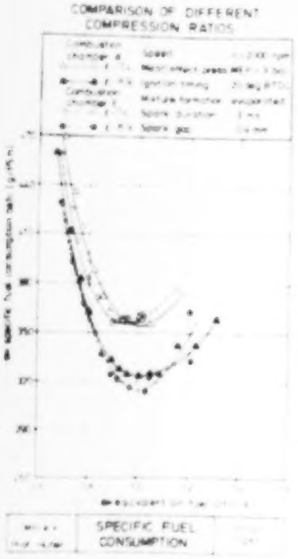

figure 9

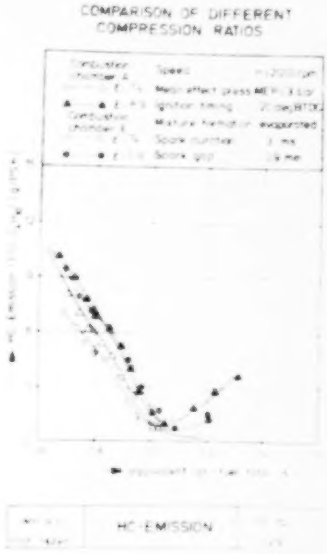

figure 10

These experiments were carried out using combustion chambers A and E. Figure 9 shows the effects on specific fuel consumption, lower compression ratio leads to a considerable loss in fuel economy. Figure 10 indicates little advantage on exhaust hydrocarbon, when using lower compression ratio. The reason for this is the reduced quenching effect, since less fuel is deposited in the quenching zones. Also, the surface to volume ratio becomes more favourable. Figure 11 shows that no substantial advantages concerning NO concentration could be found at either the lower or the higher load condition.

Change of compression ratio has an negligible influence on CO concentration.

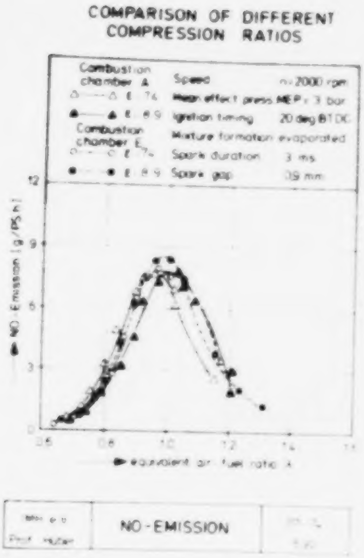

figure 11

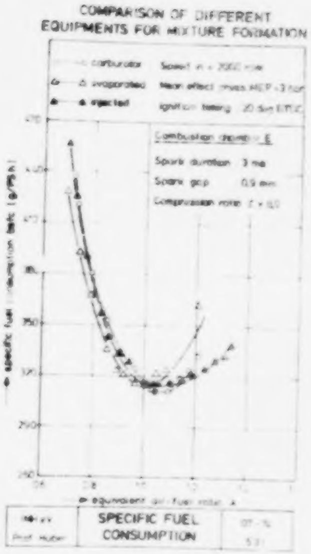

figure 12

To eliminate the possible effect of inhomogenous mixtures equipment was developed to produce a homogenous dry mixture of fuel vapour and preheated air. The intake temperature of this mixture was 50° C. Mixture formation with this type of device was compared with two conventional mixing systems: an intermittant low pressure fuel injection, ahead of the inlet valve, and a normal carburettor.

The homogenous dry mixture gives slight advantages in reduced hydrocarbon emissions, but these advantages do not justify the expensive equipment involved. There are negligible differences in specific fuel consumption, see figure 12.

Hydrocarbon emissions with the fuel injection system were considerably higher than the carburettor or homogenous mixture device, when the mixture was rich, see figure 13.

NO emission with the injection system is slightly lower than with the other two systems, see figure 14.

This trend, in which the injection system produced more hydrocarbons and less NO, appeared in all the tests undertaken. CO emission was not sensitive to the type of device used for the mixture formation.

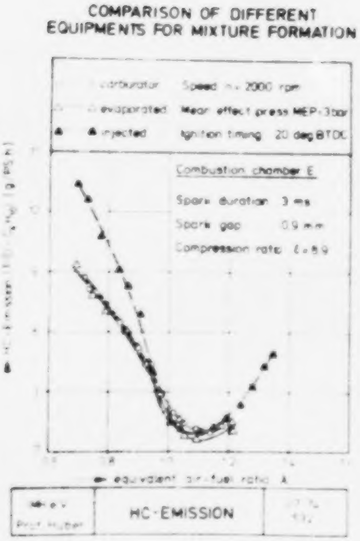

figure 13

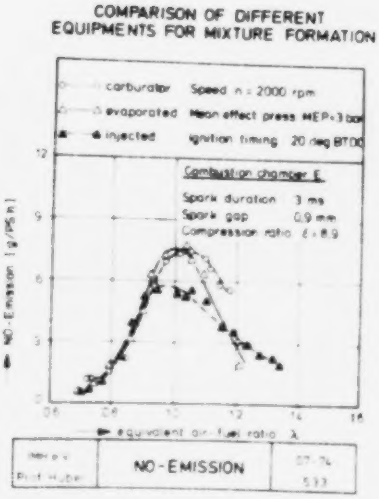

figure 14

It must be noted that these results were obtained from a single cylinder engine under steady state operating conditions. It can be expected therefore that the homogenous mixture device will show essential advantages in multi-cylinder engines, especially under transient conditions. It is apparent that the mixture quality produced by a carburettor is not inferior to those of the other two systems considered. Disadvantages in the use of a carburettor arise mainly from problems of maldistribution between cylinders and accumulation of fuel on the walls of the induction system during an engine transient.

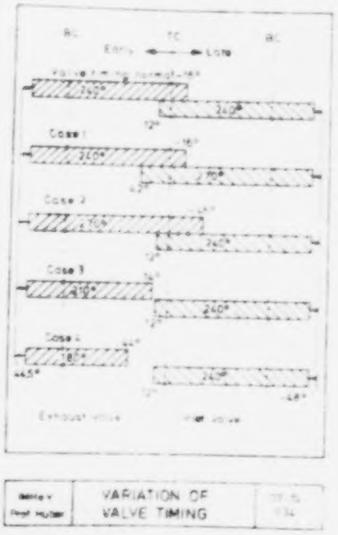

figure 15

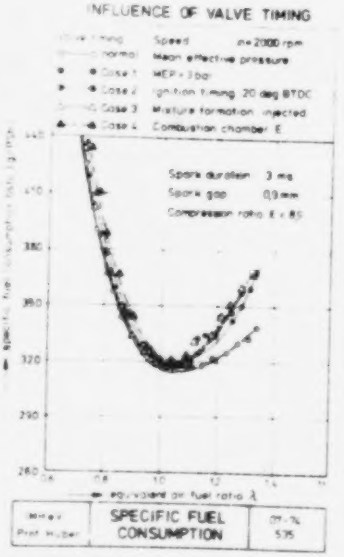

figure 16

A further influence investigated was the valve timing, see figure 15. Changes in valve timing were carried out to increase the quantity of exhaust residuals in the engine cylinder.

In case 1 the opening of the inlet valve was advanced by 30°, closing of the inlet valve and exhaust valve timing remain the same.

In case 2 closing of the exhaust valve was retarded by 30°, so that aspiration of combustion products from the exhaust system was possible.

Case 3 and 4 use shortened periods of exhaust valve opening, so that different quantities of exhaust gas are trapped in the engine cylinder. Case 3 employs an advance by 30°, and case 4 by 60°. Cases 3 and 4, particularly the latter, produce a very significant loss of maximum engine power, as a consequence of the loss of volumetric efficiency.

In all cases specific fuel consumption is a little higher than with normal valve timing, see figure 16, but the differences are not very great.

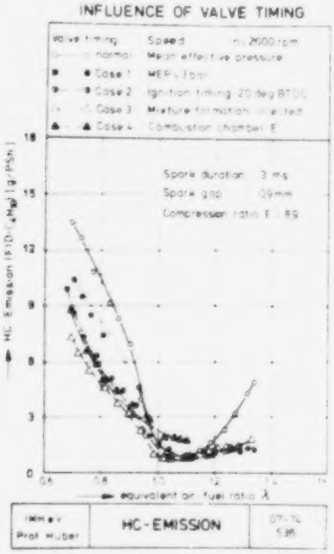

figure 17

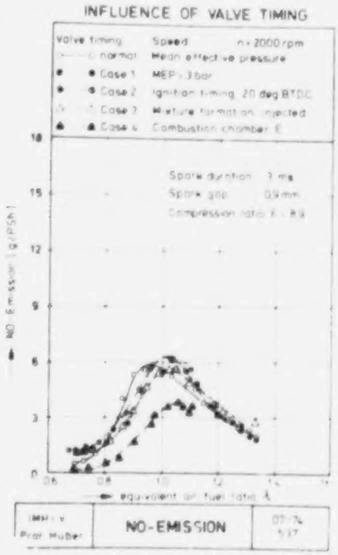

figure 18

Considerable differences appear in hydrocarbon emissions, see figure 17. Cases 2 and 4 show considerable advantages. In case 4, however, the lean operating limit is only slightly above the stoichiometric. Case 2 is most interesting, it indicates no loss in power and economy, but a significant reduction in hydrocarbon emission. CO emissions are the same in all the four cases. It can be stated therefore that the CO concentration is a function of the equivalent air/fuel ratio only. A slight influence on NO concentration was found by variing the valve timing, see figure 18. At low load and late ignition timing practically no reduction of NO appeared, with the exception of case 4. However, this changed with advanced ignition, see figure 19. A reasonable reduction of NO emission with increased exhaust gas residuals could be found.

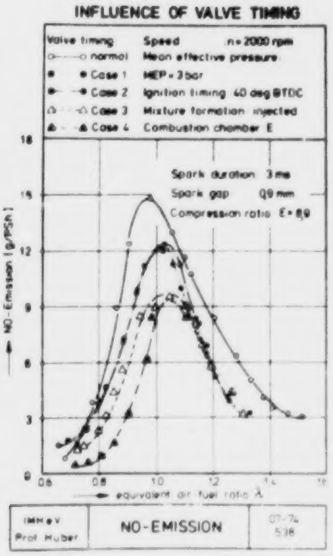

figure 19

In cooperation with the Institut für Mineralölchemie Prof. Spengler, Technical University Munich, exhaust gas samples from our test engine were analysed in detail by means of gas chromatography. Different shapes of combustion chamber and variations in injection timing and different methods for mixture formation were investigated. Pronounced differences were shown to occur in the range of the lighter compoments of the hydrocarbons up to C_4. The reason for these differences, however, could not be found.

Summing up all our results it can be stated that internal engine modifications alone can lead to a considerable reduction of noxious emissions in a spark ignited engine. Significant progress, however, can not be gained by one method alone but by using a combination of methods to produce the optimum result. In this way an essential reduction of pollution without loss in economy can be obtained in comparison with the engine of the 1960's.

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THE INFLUENCE OF IONIZATION PROCESSES ON THE REACTION KINETICS OF COMBUSTIONS

Professor Dr.rer.nat. Helmut EHRHARDT
Dipl.-Physiker Heinz GÜNTHER
Professor Dr.-Ing. Hans MAY

Universität Kaiserslautern
675 Kaiserslautern /Postfach 3o49
Germany

For the reduction of nitric oxyd in exhaust gases of combustion engines it is proposed to increase the ionization in the ignited fuel/air mixture by an electrical discharge. Theoretical estimates suggest that such a proceeding might be successful. An experimental set-up for the test of the proposal is described.

Pour la réduction de l'oxyde nitrique dans les d'engins à combustion, on propose d'augmenter très fortement l'ionisation dans le cylindre au moment de l'allumage du mélange combustible/air par la superposition d'une décharge électrique. Des estimations théoriques montrent qu'un tel processus devrait être possible. Pour vérifier, on a monté une expérience que nous allons décrire.

Zur Reduzierung von Stickoxyd im Abgas von Verbrennungsmaschinen wird vorgeschlagen, die Ionisation im Zylinder im Augenblick der Zündung des Brennstoff/Luftgemisches durch Überlagerung einer elektrischen Gasentladung stark zu erhöhen. Theoretische Abschätzungen zeigen, daß ein solches Verfahren möglich sein sollte. Zur Prüfung wurde ein Experiment aufgebaut, das beschrieben wird.

Although the natural ionization in combustions is low, electrical methods are not only of great value for diagnostics, but also practical applications are of increasing importance during the last few years. It is well known (Ref.1), that an external electrical field acts on the ions of a flame which in turn act on the neutral particles and therefore a considerable body force on the entire gas is the result. The ionic wind and the associated aerodynamic effect have been successfully applied for the enhancement of heat transfer to solid surfaces, for the suppression of flame instabilities, and for the control of carbon formation. Another wellknown application of the ionization in combustions is the seeding with alkali metals in order to raise the electrical conductivity of the combustion to the level required to operate MHD generators. Also, augmented flames (Ref.2) by D.C. and radiofrequency discharges have been used for enhancement of flame propagation or chemical processing. - To the knowledge of the present authors, augmentation of ionization in a flame to the purpose of reduction of NO pollution in exhaust gases of combustion engines has not yet been investigated theoretically nor experimentally. It is the purpose of this paper to start the investigation on this subject by quantitative theoretical arguments and to discribe an experimental arrangement for the application-close check of the proposal.

IONIZATION PROCESSES IN COMBUSTIONS

For the concept of destruction by ionization of NO molecules formed in combustions, the following facts are of importance:

i) The concentration of NO molecules in the exhaust gas of an OTTO engine (Ref.3) is about 4000 ppm if near stoichiometric conditions are valid. This concentration is high from the standpoint of pollution, but rather low compared to the sum of concentrations of all components. It is therefore possible (see below) to use comparatively small electric power for the decomposition of NO.

ii) Since in a hydrocarbon flame NO has the lowest ionization potential (9,25 eV) of all stable molecules and many radicals, the charge will be concentrated on NO^+.

iii) The decomposition process (dissociative recombination)

$$NO^+ + e^- \longrightarrow N + O$$

is ca 10^4 times faster than all possible formation processes.

In the course of the present paper these three points have to be discussed more in detail.

Natural ionization and ion reactions

The natural ion concentration in hydrocarbon-air flames is very low. Using Saha's equation for a HC-air flame at 1 atm, 2500°K, and 4000 ppm NO leads ca 5.10^9 NO^+ cm^{-3} whereas the NO concentration is $[NO] \sim 5.10^{16}$ cm^{-3}, if only direct ionization for an activation energy of 9.25 eV is considered. Of course, it is well known by now, that chemi-ionization processes as

$$CH + O \longrightarrow CHO^+ + e^-$$

$$CH^* + O_2 \longrightarrow CHO^+ + O^-$$

$$\searrow CHO^+ + O + e^-$$

and others, are more effective, since in a single step for the final formation of CH or CH^* much less energy than the ionization energy of NO is needed and the final chemi-ionization processes are often exothermic. The sum of direct ionization and chemi-ionization in HC-air flames at 1 atm lead to about 10^{11} - 10^{12} ions/cm^3 and with additives as acetylene the ion concentration may be as high as 1 ion for 10^5 carbon atoms (Ref.4), which means 10^{13} ions/cm^3 or more.

Other ions than NO^+ and those formed by chemi-ionization have higher ionization potentials and therefore their concentrations are considerable less, normaly several orders of magnitude.

Especially in low pressure flames many positive ions of different composition have been measured with a mass spectrometer, as for example

$$H_3O^+, \; H_5O_2^+, \; C_3H_3^+, \; C_2H_3O^+, \; CH_3O^+, \; CHO^+ \text{ etc.}$$

They are formed by direct and chemi-ionization or by charge exchange. Since charge exchange reactions in flames can only occur, if the reaction heat is positive or slightly negative, the charge exchange reaction chains will preferably tend to produce ions with the lowest ionization potential. Complicated ions as $H_5O_2^+$, which normaly have a low ionization potential, are destroyed in high pressure flames. Therefore, in HC-air combustions at a pressure of several atmospheres the great majority of ionic reactions should lead to NO^+.

Most of the negative charges in a flame are observed as free electrons. Although a great variety of negative ions have been found (Ref.5), their concentrations are only in the order of 1% of the concentrations of positive ions. Furthermore, detachment rates are high, so negative ions should decay at high pressures very fast according to the reaction

$$A^- + B \longrightarrow A + B + e^-$$

From the aboved mentioned processes one comes to the conclusion,that in a moderately high pressure HC-air combustion most of the positive charge is present as NO^+ and practically all negative charge as free electrons.

Recombination of charge can in principle occur in different ways:

a) neutralization on the wall of the reaction chamber

b) by 3-body collisions, as

$$NO^+ + e^- + M \longrightarrow NO + M$$

c) by radiative recombination

$$NO^+ + e^- \longrightarrow NO + h\nu$$

d) by associative recombination

$$NO^+ + O^- \longrightarrow N + O_2$$

e) by dissoziative reombination

$$NO^+ + e^- \longrightarrow N + O$$

Reactions a) ... d) can only be of little influence, since we deal with a combustion at relatively high pressure (a) recombination rate have been measured to be practically independent of pressure (b), radiative recombination has a cross section of ca $10^{-20} cm^2$ (c), and negative ions a rare in such a combustion (d). The only important reaction should be the dissoziative recombination with a cross section of ca $10^{-13} cm^2$ or a rate constant of ca $10^{-7} cm^3 sec^{-1}$ (Fig.1). But this reaction leads to the dissoziation of NO.

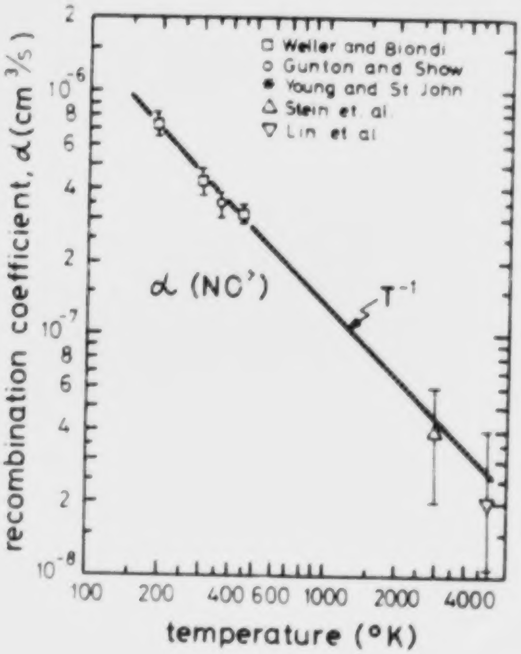

Fig. 1 Temperature dependence of the recombination rate constant of (NO^+, e^-)

If a lead compound is used in the fuel, then the recombination is strongly reduced (Ref.6), probably by about two orders of magnitude, since

a) charge exchange processes lead preferably to Pb^+, e.g.

$$Pb + H_3O^+ \longrightarrow Pb^+ + H_2O + H, \quad H = + 20 \text{ Kcal}$$

because of the low ionization potential of Pb

b) the three body recombination is then probably the fastest process

$$Pb^+ + e^- + M \longrightarrow Pb + M$$

Augmentation of ionization

Since the natural ionization in HC-air flames is low even with HC-additives, at the most 0.1% of the NO is decomposed via the electronic dissoziative recombination. A reduction of the NO concentration, which is of interest for practical applications,is only to be expected by this method, if most of the NO molecules are ionized. For a 1.5 liter engine about 10^{19} molecules are formed per cylinder and per ignition. In order to ionize most of these molecules, probably 5 to 7% of the mechanical work of the cylinder has to be put into the combustion as electrical work (ca 1.5 KW); the degree of ionization of the gas is than still less than 1%.

These numbers look encouraging, but there are two important questions, which finally only can be answered experimentally. These questions are:

i) Will the electrical energy in the course of its degradation mostly be transfered into translational energy of the neutral gas and therefore be available for mechanical energy and what fraction actually leads to ionization?

ii) How looks the spacial distribution of a gas discharge in a combustion with a rather well developed flame front?

With respect to the first question it must be considered that only a fraction of the electrons, which are accellerated in the electric field are available for further ionization, the others will loose energy by excitation of rotation (cross section ca 10^{-17}cm^2 for dipol molecules), by excitation of vibrations mostly via shortliving negative ion states, e.g.

$$e^- + N_2 \longrightarrow N_2^- \longrightarrow N_2^* \text{ vibration} + e^-$$

Similarly other molecules like O_2, NO, H_2O, CO_2 are vibrationally excited. The electron looses energy in such collisions in the range between 0 and about 3 eV. The cross sections are typically 10^{-15} - 10^{-17}cm^2. Since a particle makes about 10^7 - 10^8 collisions during one cycle of an engine, rotations and vibrations will be in equilibrium with translation of the surrounding gas. With respect to electronic excitation there is no difference compared to an ordinary combustion without electrical discharge. The dissoziative recombination of NO^+ leads to two fast neutral atoms, which transfer their translational energy very fast into translation of their neighbour particles. In so far, the first part of the question seems to be answered that practically all electrical energy is transfered to heat. Of course, little overpopulation and a few metastable particles will leave by the exhaust. The second part of the question cannot reliably solved even by a thorough calculation. Experiment must be awaited.

With respect to the second question, a volume discharge is expected since the flame front creates a relatively large number of ions and electrons, which in turn are accelerated by the applied field. If, of course, a threadlike electrical breakdown would occur, then the effect on the NO-concentration would be negligible. Also here, only experiment can give the answer.

EXPERIMENTAL SET-UP

An apparatus is being build up for the test of the proposal. Part of it is finished and experiments have started. A schematic diagram is given in Fig. 2

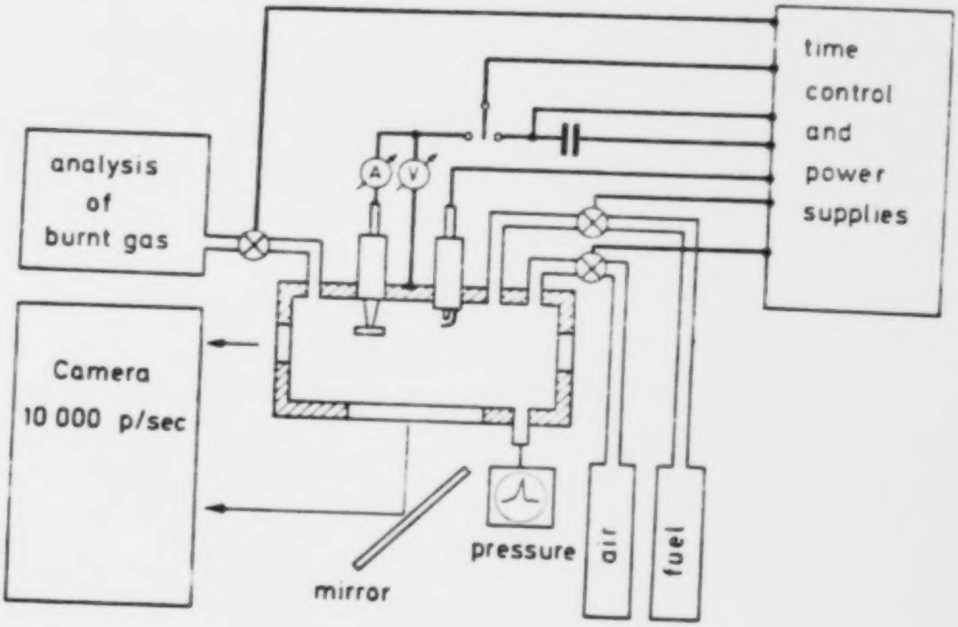

Fig. 2 Schematic diagram of the apparatus.
The diameter of the reaction chamber is 8o mm, its height 2o mm.

The reaction chamber has constant volume. It is intended to change to a one-cylinder machine with movable piston as soon as positive results are obtained with the present arrangement. A stoichiometric methane/air mixture is admitted through magnetic valves, which are controlled by a time steering unit; also time controlled are the spark ignition, the opening of the exhaust valve, and of course the time at which the high voltage is applied to the electrode inside the reaction chamber. The time dependences of the high-voltage-decrease and the current flowing during the combustion as well as the pressure increase is measured with oscilloscopes. A high speed camera with lo^{4} photographs sec^{-1} is able to visualise the propagation of the flame front and the spacial shape of the discharge. The exhaust gas analysis is not yet possible. For additional measurements (temperature etc.), which might be necessary in the future, windows and feed throughs are foreseen.

Out of the few measurements, which could be made up to now, the most important result is, that volume gas discharges were obtained of ca 1.5 KW electric power with a duration of ca 5 msec. for about 15 KV applied voltage and for a charging pressure of the methane/air mixture of ca 2 atm. During the combustion the pressure raises to approximately lo atm (Fig.3)

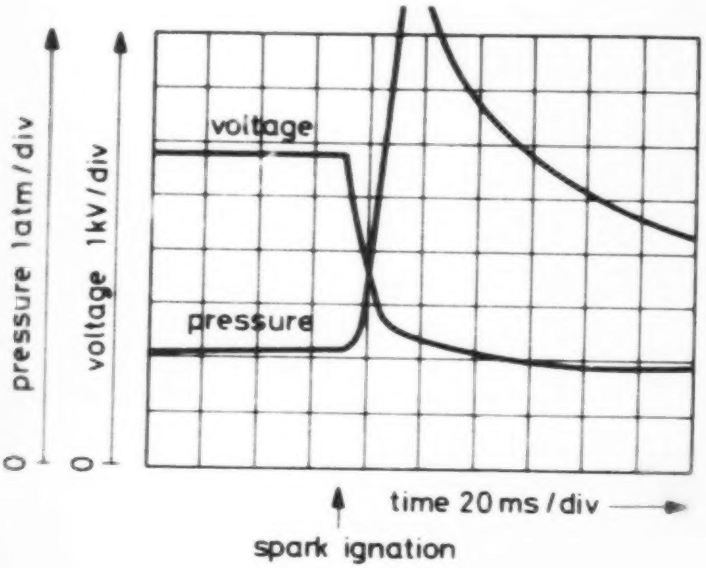

Fig. 3 Simultaneous tracing by an oscilloscope of the time dependences of the pressure and the high voltage. The discharge current is equal to the time derivative of the high voltage multiplied by the capacity of 2·lo^{-6} Farad.

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Possibilities of Lowering NO-Emissions of Spark-Ignition Engines Discussed by Kinetical Modeling of the Engine Process

Professor Dr.-techn. F. PISCHINGER
Dr.-Ing. W. KLEINSCHMIDT

Lehrstuhl für Angewandte Thermodynamik, RWTH Aachen

For spark ignition engines a calculation model incorporated into a computer program was developed. The model calculates the exhaust gas pollutant concentrations and the indicated mean effective pressure and efficiency. In this paper the model is used to discuss various methods of NO-control as modifications of engine operating conditions, exhaust gas recirculation and charge stratification.

Des modéles et des programmes de calculation ont été évolués pour pouvoir simulier le procés du moteur Otto en vue du comportement de sa puissance, de son éffectivité et de ses émissions.
Des plusieurs mésures internes du moteur pour réduire les émissions oxyde nitrique ont été comparé à l'aide des resultats des calculations de simulation. On discutera et expliquera ici les éffets sur les allures, qui aménent à l'émission de oxyde nitrique. Sur cette base il est possible de prendre une position fondée sur le probléme de réduction des émissions oxyde nitrique à travers des mésures internes de moteur.

Es wurden Rechenmodelle und Rechenprogramme entwickelt, die es ermöglichen, den Arbeitsprozeß von Ottomotoren hinsichtlich seines Leistungs-, Wirkungsgrad- und Emissionsverhaltens zu simulieren.
Anhand der Ergebnisse von Simulationsrechnungen werden verschiedene innermotorische Maßnahmen zur Verringerung der Stickoxidemission wie z.B. Veränderung der Motorbetriebsparameter, Abgasrückführung und Gemischschichtung einander gegenübergestellt. Dabei werden jeweils die Auswirkungen auf die zur Stickoxidemission führenden Vorgänge diskutiert und erläutert.

1. Introduction

The increasing efforts to reduce emissions from spark-ignition engines have made desireable the use of mathematical models of the engine process in order to get a better understanding of the pollutant formation mechanism inside the engine cylinder. Much work in this field has been concerned with the theoretical prediction of NO-concentrations in the engine exhaust gas /1, 2, 3, 4/. However, till now it was not possible to obtain good agreement between predicted and measured exhaust NO-concentrations for a wide range of engine operating conditions. As a part of the research work in the Institute of Applied Thermodynamics, Technical University Aachen, a sophisticated model of the spark-ignition engine process has been developed. This model incorporated into a computer program avoids some simplifying assumptions introduced into the calculations known so far. It predicts correctly the exhaust pollutant concentrations over a wide range of engine operating conditions. In addition to the pollutant concentrations the model calculates the indicated mean effective pressure and the efficiency of the engine process. Therefore the model predictions may be valuable in the discussion of methods of NO control.

2. Model of engine combustion

In the following, some characteristics of the model concerning the combustion process are briefly summarized. A detailed description of the model developed for the cycle of spark ignition engines is given in / 6 /.

During combustion the propagating flame is assumed to be infinetely thin and to divide the combustion chamber into two regions (Fig. 1). The region already passed by the flame contains the dissociated combustion gases of high temperature (post-flame gas) and the region not yet reached by the flame contains the unburnt mixture. One important feature of the combustion process inside the engine are the temperature and concentration gradients within the burnt gases resulting from the progressive burning of the charge and the different temperature-time histories of different charge elements. To account for these burnt gas nonuniformities it was assumed that charge elements which burn at different times do not mix but retain their identity during the whole combustion

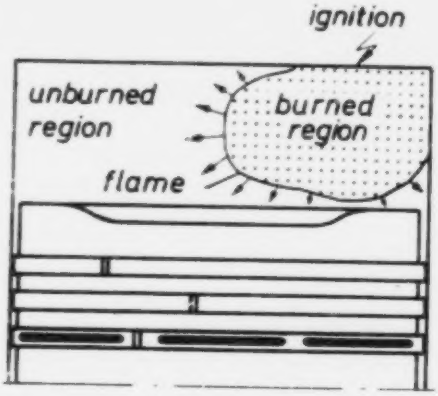


Fig. 1: Model of flame propagation

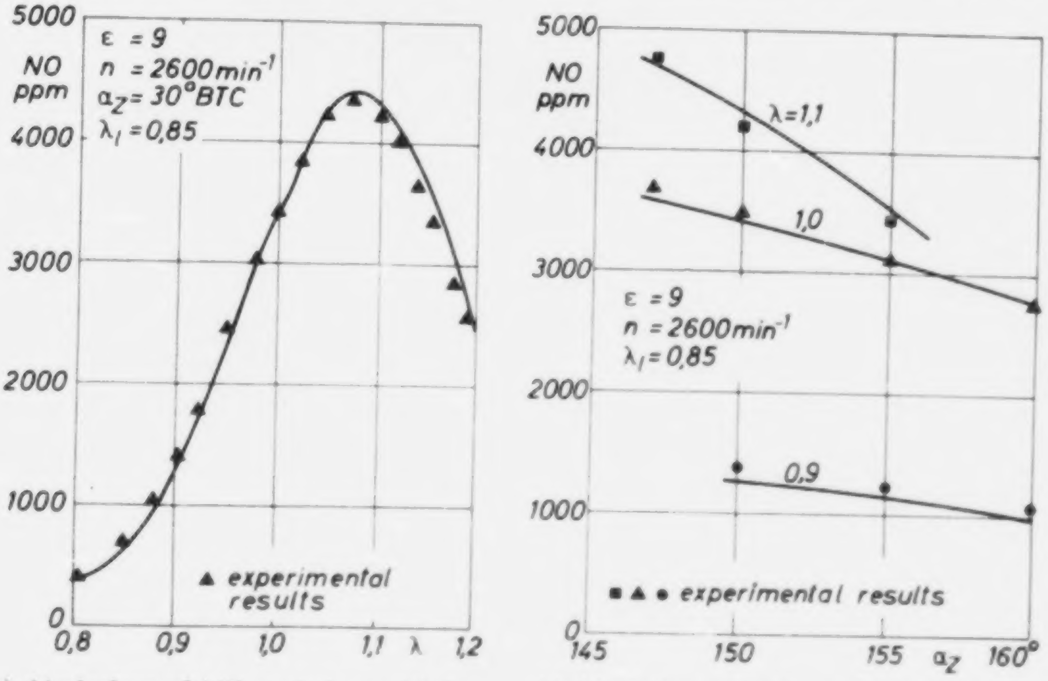
process. Consequently, at any time during combustion each element has its own NO-concentration. The instantaneous NO-concentration can be calculated by integrating across the charge.

The mechanism of flame propagation inside the engine cylinder cannot be treated analytically at present. Therefore the calculation of the combustion process is based on the specification of a "burning function" $x = m_b/m = f(\alpha)$ (see list of symbols).

The elementary reactions used to describe the post-flame reaction processes are listed in Table 1. Most of the kinetic data were taken from / 5 /. As can be seen from Table 1. no equilibrium assumptions for the O-H-C chemistry were introduced into the model. Thus the model also yields predictions of CO- and NO_2-concentrations in the engine exhaust gas. A summary of all computer program input and output data is given in Table 2.

3. Comparison of model predictions with NO-measurements

The model predictions are compared with exhaust NO-concentrations measured on a single cylinder AVL engine. For variations of the relative air-fuel ratio and ignition timing the results are presented in Fig. 2 a and b, respectively. The burning functions required for the calculations were obtained from measurements of cylinder pressure versus crank angle for representative average-cycles and are shown in Fig. 3 a and b.



a) Variations of NO-emissions with λ b) Variations of NO-emissions with α_z

Fig. 2: Experimental and calculated exhaust gas NO-concentrations.

O-H-C-reactions

radical exchange reactions	dissociation and recombination reactions
1) $CO + OH \rightleftharpoons CO_2 + H$	6) $OH + M \rightleftharpoons O + H + M$
2) $H_2O + H \rightleftharpoons H_2 + OH$	7) $H_2 + M \rightleftharpoons H + H + M$
3) $O_2 + H \rightleftharpoons OH + O$	8) $H_2O + M \rightleftharpoons H + OH + M$
4) $H_2 + O \rightleftharpoons OH + H$	9) $CO_2 + M \rightleftharpoons CO + O + M$
5) $OH + OH \rightleftharpoons H_2O + O$	10) $O_2 + M \rightleftharpoons O + O + M$

N-O-H-reactions

11) $N_2 + O \rightleftharpoons NO + N$	16) $N_2O + M \rightleftharpoons N_2 + O + M$
12) $O_2 + N \rightleftharpoons NO + O$	17) $NO + NO \rightleftharpoons N_2O + O$
13) $OH + N \rightleftharpoons NO + H$	18) $NO + O + M \rightleftharpoons NO_2 + M$
14) $N_2 + O_2 \rightleftharpoons NO + NO$	19) $NO_2 + O \rightleftharpoons NO + O_2$
15) $NO + M \rightleftharpoons N + O + M$	20) $N_2 + M \rightleftharpoons N + N + M$

Table 1: Post-flame reactions

input data	output data
engine dimensions, compression ratio, relative air-fuel ratio, spark timing, engine speed, intake conditions, valve timing, burning function (burned mass fraction vs. crank angle), composition and thermodynamic data of fuel, cylinder wall temperature.	burned gas concentrations of species O, H, CO, O_2, H_2, H_2O, CO_2, OH, N_2, N, NO, NO_2, N_2O and burned gas temperature as function of crank angle and mass coordinate; cylinder pressure, temperature of unburned mixture in front of the flame, heat and work as function of crank angle; indicated mean effective pressure and efficiency; exhaust gas fraction in the intake mixture; losses of available energy due to irreversible processes.

Table 2: Computer program input and output data

The agreement between calculated and experimental exhaust NO-concentrations is good. Similar agreement was obtained for variations of other engine operating parameters without any fitting of kinetic reaction rate data or atomic oxygen concentrations as was found to be necessary in other calculations to match experimental data / 4 /. Thus the model seems to contain sufficient representation for the processes responsible for NO formation and it may be useful for discussion of methods to reduce the NO-emissions of spark-ignition engines.

4. Discussion of methods of NO-control

Model calculations have shown, that the NO-formation rates during engine combustion are mainly determined by the concentrations of atomic oxygen reached in the post-flame gases / 6 /. This follows from the fact, that in high temperature systems the elementary reaction $N_2 + O \rightleftharpoons NO + N$, responsible for breaking the N - N bond, is the rate determining step of NO-formation. Therefore, to reduce NO-formation the post-flame gas O-concentrations must be lowered and the residence time of the post flame gases at high O-concentrations must be reduced.

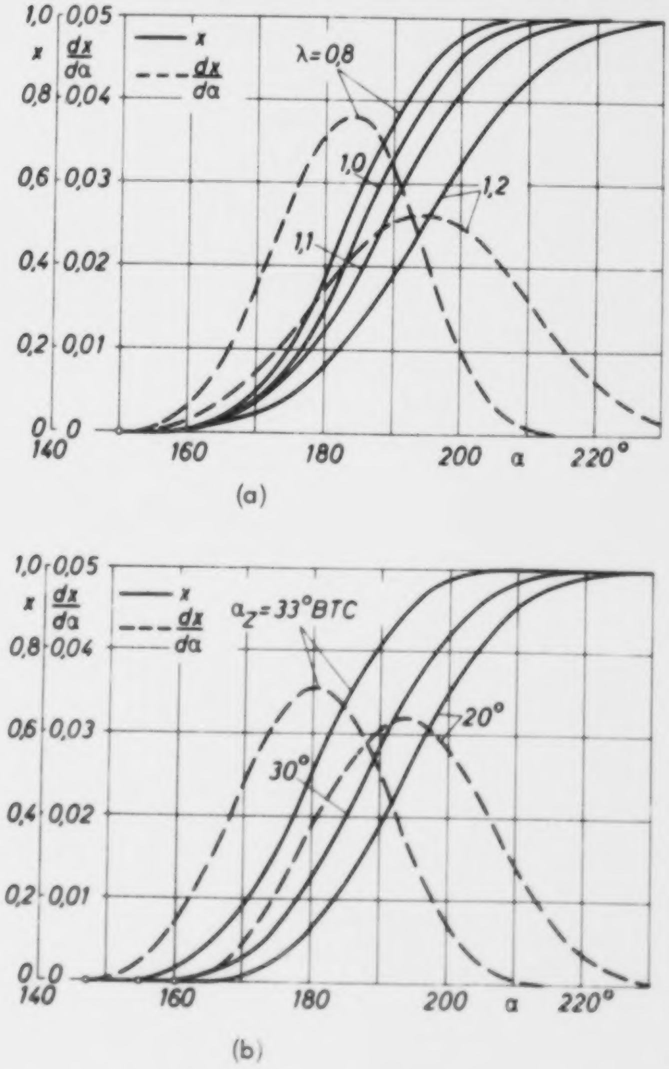


Fig. 3: Burning functions corresponding to Fig. 2

4.1. Modification of engine operating parameters

It is known, that the NO-emissions of spark-ignition engines are considerably affected by the engine operating conditions. From this view it may be interesting to ask for the reductions of NO-emissions that can be achieved by suitable control of the engine combustion process on condition that there is no loss of power and efficiency. This question can be answered in general. During conventional engine combustion the first burnt part of the charge reaches considerably higher temperatures than the part burnt later in the process. High temperatures favour dissociation of molecular oxygen to atomic oxygen, thus leading to increased rates of NO-formation in the first burnt part of the charge. To reduce the post-flame formation of NO any temperature rise in the post-flame gases must be avoided. This can be accomplished (without losses of power and efficiency) by an engine process which has the following features:

1) High compression ratio (to achieve sufficiently high temperatures of the unburnt mixture, necessary for good efficiency)
2) Ignition in the vicinity of the top dead center
3) Combustion at approximately constant pressure.

In this case, there exists no temperature gradient across the burnt gases and the post-flame temperature remains constant during the whole combustion process. A set of pressure versus crank angle curves which come near to the ideal engine process defined above is shown in the upper part of Fig. 4 for different values of the compression ratio ε . For comparison the pressure versus crank angle curve of a conventional engine cycle was also introduced into the figure. The lower part of Fig. 4 shows the corresponding NO-concentrations (mole-fractions) calculated for each charge element at crank angle $\alpha = 80^\circ$ ATC. The abscissa is the burning function. $x = 0$ corresponds to the first burnt element and $x = 1$ to the last burnt element of the charge. Averaged NO-concentrations are indicated by dotted lines. As can be seen from the figure the ideal process with $\varepsilon = 16$ has the same indicated efficiency η_i (and mean effective pressure - not shown in Fig. 4) as the conventional engine process with $\varepsilon = 9$. However, NO-emissions have been reduced by about 40 %. Of course, we are aware, that it might be difficult to achieve this ideal processes in engine-practice.

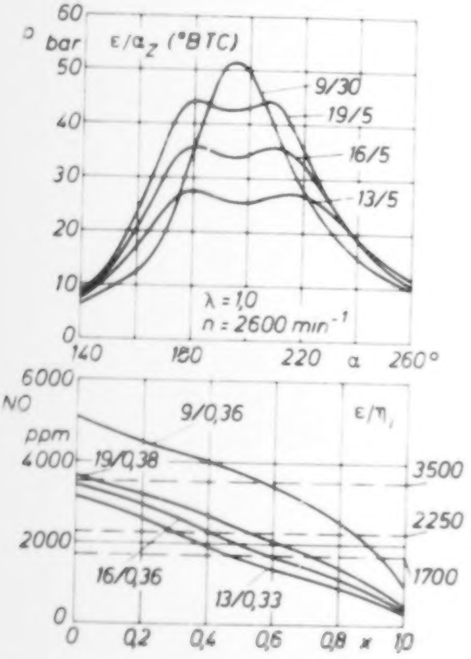


Fig. 4: NO-emissions from engine combustion at approximately constant pressure

4.2. Exhaust gas recirculation

For a given relative air-fuel ratio the post-flame gas O-concentrations are determined by gas temperature only. Recycling of cool exhaust gas to the intake mixture yields decreased gas temperatures and O-concentrations and therefore decreased rates of NO-formation. Fig. 5 shows the exhaust gas NO-concentration as function of the relative air-fuel ratio, calculated for different exhaust gas fractions in the intake mixture. The calculations are based on burning functions (Fig. 6) obtained from experiments. As can be seen from Fig. 5 exhaust gas recirculation yields considerable reductions of NO-emissions, provided the level of recirculation is high enough.

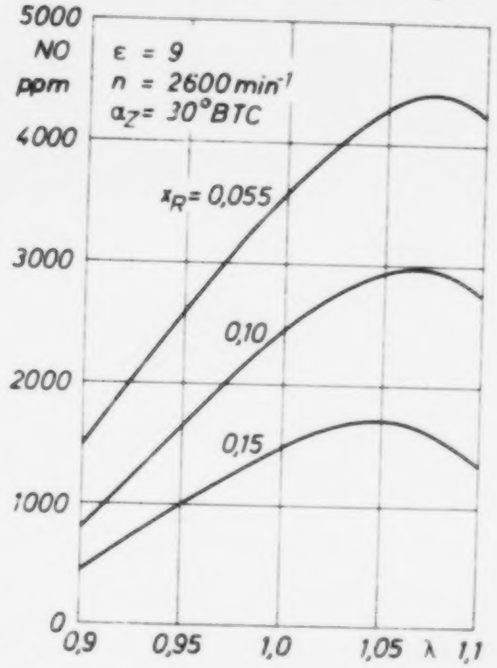


Fig. 5: Variations of NO-emissions with x_R

Quite similar to an increase of the relative air-fuel ratio, exhaust gas recirculation results in the lengthening of the combustion period (s. Fig. 6). Regarding this, the indicated efficiency of the engine process might be expected to decrease with increasing exhaust gas recirculation. However, engine measurements indicate constant efficiency for moderate recirculation rates. This fact can be explained by the model calculations. Up to a critical amount of exhaust gas recirculation its diminishing influence on efficiency is compensated by decreasing heat losses to the cylinder walls due to decreasing burnt gas temperatures during combustion and expansion.

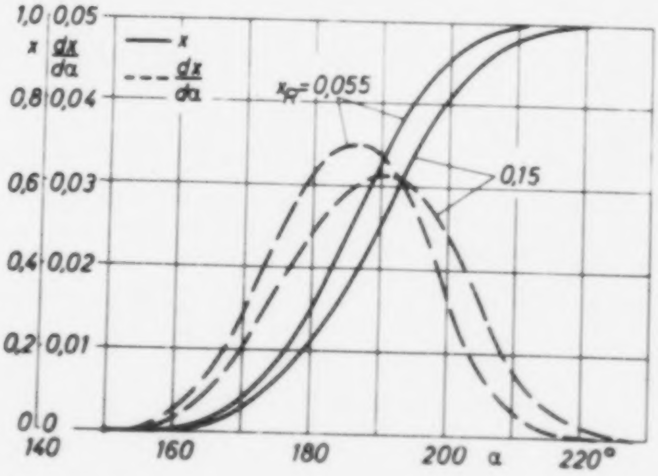


Fig. 6: Burning functions corresponding to Fig. 5

With increasing relative air-fuel ratio the maximum allowable exhaust gas fraction in the intake mixture decreases. For $\lambda \approx 0,9$ exhaust gas fractions up to 20 - 25 % are permissable without loss of efficiency. In lean mixtures, however, also low recirculation rates would result in decreasing efficiency. For a given engine increasing exhaust gas recirculation reduces the air and fuel rates, thus leading to an increased loss of mean effective pressure.

4.3. Charge stratification

During normal engine combustion the first burnt part of the charge, being the hottest, reaches relative high concentrations of atomic oxygen and therefore preferably contributes to NO-emissions. Nowadays, charge stratification is expected to be a very effective way to reduce NO-formation in this part of the charge. The concepts of charge stratification can be summarized as follows: A fuel-rich mixture is set up in the part of the charge being close to the spark plug while the rest of the combustion chamber contains a fuel-lean mixture. The charge elements burning first after the onset of combustion reach the highest level of burnt gas temperature and with respect to the late burning elements have relatively long residence times at process peak temperature. However, because of the low relative air-fuel ratio in this part of the burnt gas region dissociation to atomic oxygen is suppressed thus leading to reduced rates of NO-formation.

The calculation model, originally developed for engines burning a homogeneous mixture, can also be used to estimate the effectiveness of charge stratification on reducing NO-emissions. Fig. 7 compares the NO-profiles calculated for a homogeneous mixture and two different processes with charge stratification. The calculations were carried out by using the λ-distributions shown in the lower part of the figure. (All distributions have the mean value $\bar{\lambda} = 1$.) The abscissa is the burning function, acting here as a "mass-coordinate" (quite similar to the lower part of Fig. 4). Apparently the amount of NO-reduction against the normal process is considerably affected by the shape of the λ-distribution. The lowest mean NO-concentration was calculated for the step function of the λ-distribution. Extension of the transitory region between λ_{min} and λ_{max} results in increased NO-emissions. This also can be seen from Fig. 8. The ordinate is the NO-concentration in the exhaust gas and the

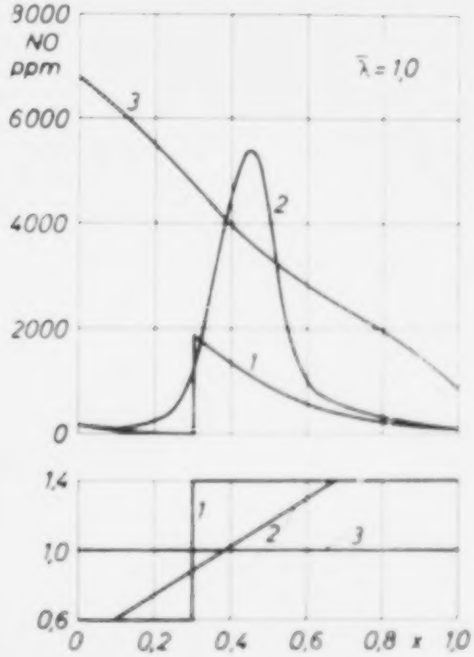


Fig. 7: NO-profiles calculated for different λ-distributions

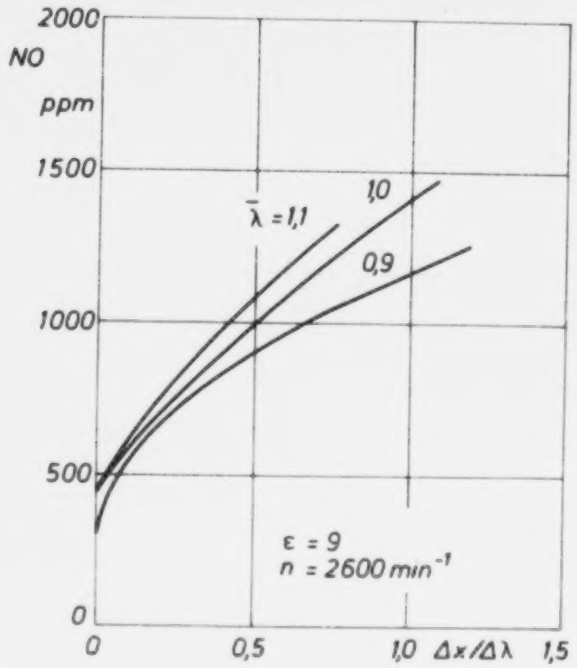


Fig. 8: NO-emissions calculated for different λ-distributions and different mean values $\bar{\lambda}$

abscissa is the reciprocal slope of the transition from λ_{min} to λ_{max} which has been assumed to be linear for simplicity. $\Delta x / \Delta\lambda = 0$ corresponds to a step function. The curve parameter is the mean value of the relative air-fuel ratio. It can be concluded from Fig. 8 that the mean relative air-fuel ratio should have only little influence on the NO-emissions of engines with charge stratification.

4.4. Conclusions

From a kinetic and thermodynamic point of view, combustion at constant pressure, perhaps combined with exhaust gas recirculation presents one attractive method for reduction of engine NO-emissions. However, especially with respect to isobaric combustion there would raise a lot of problems in combustion control so that it might be impracticable at all. Gross reductions of NO-emissions by exhaust gas recirculation alone require high rates of recirculation thus leading to an appreciable loss of indicated mean effective pressure. In addition it seems to be uncertain that the NO-emission standards in the future can be met by exhaust gas recirculation only. Model calculations indicate that charge stratification engines in optimal design may be the most effective way to reduce NO-emissions.

List of symbols

α	crank angle	λ	relative air-fuel ratio
α_z	ignition point	$\bar{\lambda}$	mean relative air-fuel ratio
ε	compression ratio	λ_l	volumetric efficiency
η_i	indicated efficiency	n	engine speed
x	burning function (mass-coordinate)	m_b	mass of burnt gases
x_R	exhaust gas fraction	m	mass of cylinder charge

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Minimization of exhaust emissions of SI-engines; interrelating effects of air/fuel-ratio, mixture preparation, ignition, EGR and thermal and catalytic treatment of exhaust gas*)

Dr. rer.nat. H. JAHNKE, Dr.-Ing. R. LATSCH, E. LINDER, K. NEIDHARD,
D. SCHERENBERG
ROBERT BOSCH GMBH, Stuttgart

Exhaust emissions can be reduced by vaporization of the fuel during the warm-up period. If intermittent fuel injection into the inlet manifold is used the moment of injection is also decisive. - A family of characteristic curves for the ignition point and the air-fuel-ratio shows that it is impossible to minimize fuel consumption and exhaust emissions simultaneously. - Engines with subdivided combustion chambers make it possible to ignite homogeneous lean mixtures later than in standard engines. - In order to monitor catalysts and also EGR we started to develop a NO_x-sensor.

Lorsque les moteurs fonctionnent à chaud, les émissions de matières toxiques peuvent être réduites par vaporisation du combustible.Si on a une injection intermittente dans le collecteur d'admission, le choix du point d'injection joue aussi un rôle décisif. - Les courbes caractéristiques du point d'allumage et du rapport entre l'air admis et l'air nécessaire à la combustion stœchiométrique montrent que les exigences d'obtention de la consommation minimale de combustible et des émissions minimales de substances toxiques ne peuvent être remplies simultanément. - Sur les moteurs à chambre de combustion compartimentée,il est possible d'allumer plus tard des mélanges homogènes ayant des rapports plus élevés entre l'air admis et l'air necessaire à la combustion stœchiométrique.- Pour le contrôle des catalyseurs un détecteur d'oxydes d'azote a été mis à l'étude.

Durch Kraftstoffverdampfung können die Schadstoffemissionen während der Warmlaufperiode reduziert werden.Bei intermittierender Saugrohreinspritzung ist dabei auch die Wahl des Einspritzzeitpunkts entscheidend. - Ein Kennfeld für Zündzeitpunkt und Luftzahl zeigt, daß sich die Forderungen nach minimalem Kraftstoffverbrauch und minimalen Schadstoffemissionen nicht gleichzeitig erfüllen lassen. - Bei Motoren mit unterteiltem Brennraum ist es möglich, homogene Gemische bei höheren Luftzahlen später zu zünden. - Für die Überwachung von Katalysatoren oder der Abgasrückführung wurde mit der Entwicklung eines NO_x-Sensors begonnen.

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1. The influence of mixture preparation on exhaust emissions during warm-up

When intermittent fuel injection into the intake manifold is used and the fuel is injected in such a manner as to be vaporized on the hot surfaces of the intake valve and the intake manifold (fig.1), there are no advantages to be gained from a further improvement of the mixture preparation [1]. This statement is valid only for a warm engine; when the engine is cold the fuel deposited before the intake valve cannot vaporize there. In this case an additional vaporizer may be advantageous [2].

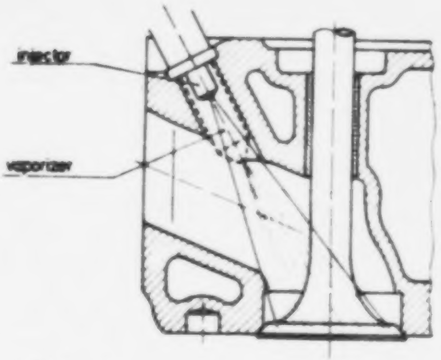

Fig. 1

The first important difference between a warm and a cold engine shows itself when selecting the optimum moment of injection (fig.2). When the engine is warm the depositing of fuel in front of the closed intake valve is useful. In a cold engine depositing, e.g. injecting at a crankshaft angle of 90° before input top dead center causes higher emissions especially of CO than injection at 0° before input top dead center.

While in the first case fuel is injected into air which is more or less at rest in the second case fuel is injected into an air flow so that less fuel has the chance to condense on the surface of the intake manifold. Therefore, the engine starts later when fuel is deposited. The fuel which is deposited in the intake manifold at the beginning of the starting procedure vaporizes with increasing vacuum and temperature when the engine is speeding up. It acts as a delayed additional enrichment.

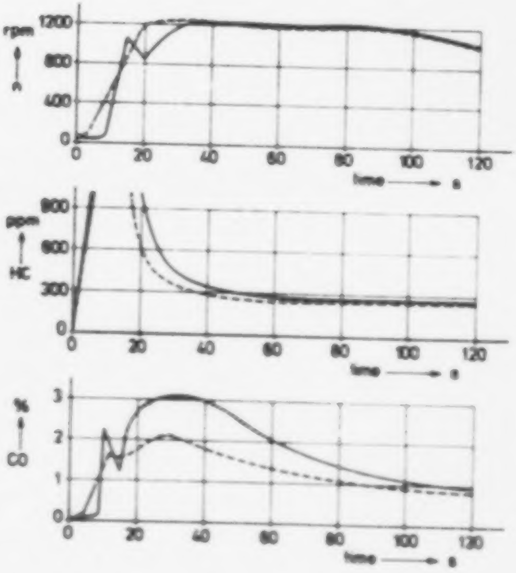

Fig. 2

Warm-up with and without fuel deposition

——— injection point 90° BTC

----- injection point 0° BTC

starting at 20° C ambient air temperature, idling conditions

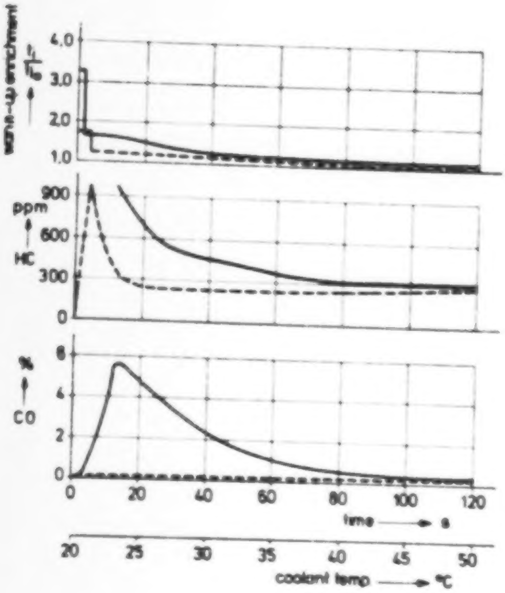

Fig. 3

Initial start and warm-up

—— without fuel vaporization
----- with fuel vaporization

optimized at 20° C ambient air temperature, idling conditions

Without fuel vaporization short starting times and therefore lower HC-emissions are only feasible when substantial enrichment is used. When the duration of this enrichment is too long, high CO- and HC-emissions are measured in the ensuing warm-up period. The upper part of fig. 3 shows the enrichment in the warm-up period, optimized to obtain the lowest exhaust gas pollution as a function of coolant temperature for an engine with and without fuel vaporization. Best results were achieved with a short start injection and sucessively reduced enrichment as coolant temperature increased. We found that the starting and warm-up enrichment can be reduced considerably by the use of vaporized fuel. The result is a distinctly reduced emission of HC and CO. Nevertheless, an enrichment remained necessary even when using vaporized fuel, though a preheating time of 20 sec. ensured that only vapor was injected from the beginning of the starting procedure onwards.

2. The interaction of ignition and air/fuel-ratio

2.1 The influence of air/fuel-ratio (A/F) and ignition point

Measurements to establish the family of characteristic curves were carried out on a 1.9 litre 4 cylinder spark ignition engine. These measurements aimed at establishing those characteristic curves for the ignition point and λ as functions of load and engine speed, which give "optimum" results concerning fuel consumption and emissions without exhaust gas treatment. The data were then prepared to be evaluated in different ways by means of computer. Fig. 4 shows curves of constant fuel consumption and constant emission as a function of ignition point and λ.

The slope is indicated by arrows. The correlation shown here was evaluated for 65 different points of the characteristic curve family. The individual results can be combined by the computer in order to plot theoretic characteristic curves for the ignition point and λ with respect to various

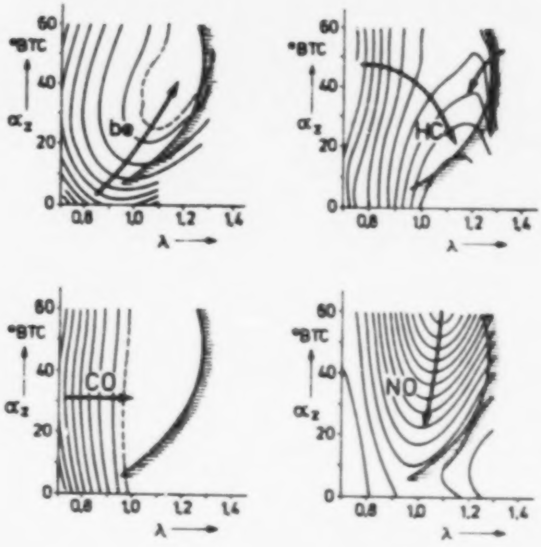

Fig. 4

Curves of constant fuel consumption b_e and constant mass-emissions versus λ and advance-ignition-angle α_z . The arrows are indicating the slope. Lean misfire limit, measured with transistorized ignition system spark duration: 2 ms; gap widths of the spark plug: 0,7 mm

criteria. For these curves average values of fuel consumption and emissions were calculated. Fig. 4 shows that the demands for minimum consumption and minimum emissions cannot be fulfilled simultaneously. For minimum HC- and NO-emissions the ignition point must be very much later and the air factor must be smaller than for minimum fuel consumption. To get "optimum" results characteristic curves were synthetized with respect to the following conditions:

- λ must exceed $\lambda = 1$ and must lie between the HC-minimum and the lean misfire limit. At the lean misfire limit minimum values of fuel consumption and NO_x-emissions are achieved.
- Ignition timing must be as "late" as possible when driving in town regions (power output < 37 kW) with respect to NO- and HC-emissions, and as "early" as possible to obtain advantageous fuel consumption when driving in the upper power output region.

The results of several computer calculations were "optimum" adjustment curves for ignition timing and λ. These curves were found to be very similar to the adjustment curves realized nowadays. The latter curves show a slightly greater safety margin from the lean misfire limit and from the knocking limit.

In fig. 5 the calculated mean values using these curves are compared with the values of minimum fuel consumption. Using "optimum" curves HC-emissions are reduced by 40 % and NO-emissions by 25 % compared with an adjustment aimed at minimum fuel consumption. The disadvantage of such an adjustment is an increase in fuel consumption of about 4 %.

The comparison is based on mean values and virtually stationary conditions.

Fig. 5: Comparison of the calculated mean values

establishment of characteristic curve	fuel consumption	exhaust emissions		
		CO	HC	NO
for minimum fuel consumption	100	100	100	100
for optimum fuel economy and optimum emissions	104	100	60	75

Partial load or warming-up conditions are omitted though such situation are of great influence on the subject.

2.2 The influence of mixture movement and turbulence in the combustion chamber

When adjusting our Jetronic-systems to various engine types we realized that the lean misfire limit is reached at λ-values varying between $\lambda = 1{,}05$ and $\lambda = 1{,}25$ depending on the shape of the combustion chamber and on the spark plug position. Mixture movement and turbulence in the combustion chamber are of great influence.

The aim is to achieve uniform mixture movement at the spark plug at the moment of ignition [3, 4, 5, 6, 7] and to then accelerate the combustion process by rapid mixture movement and turbulence. For practical investigations a 2.1 litre 4 cylinder turbulence chamber diesel engine was adapted to use spark ignition (fig. 6). Compression was reduced from $\varepsilon = 22$ to $\varepsilon = 8.5$. The engine was equipped with a standard coil ignition system, a throttle valve and intermittent fuel injection into the intake manifold (D-Jetronic). The research for the optimum ignition timing had the results shown in fig. 7: The ignition timing for maximum torque lies 10° - 12° later than for a standard petrol engine.

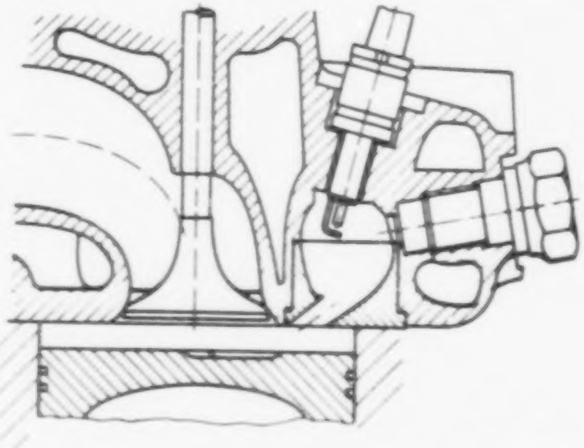

Fig. 6

Turbulence chamber engine -
compression ratio: 8.5
piston displacement: 2,067 cm^3
total cylinder volume when the upper dead center is reached: 68.8 cm^3
volume of turbulence chamber: 16 cm^3

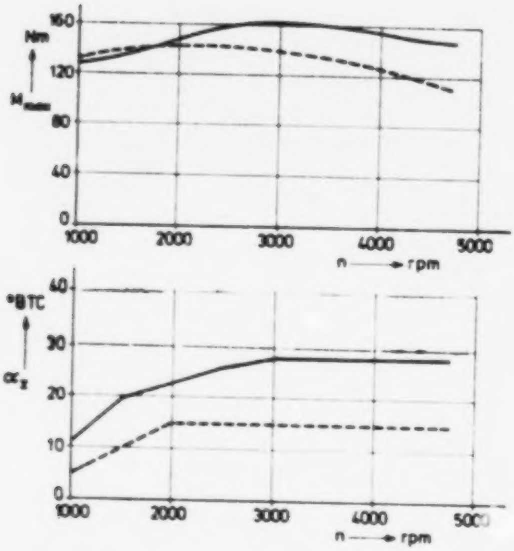

Fig. 7

Ignition angle α_z for maximum torque

—— engine without turbulence chamber

----- engine with turbulence chamber (fig. 6)

Furthermore, it is independent of engine speed beyond 2000 rpm, so that combustion is accelerated and more closely related to mixture movement which increases with increasing engine speed. Running quality is similar to a diesel engine. The reduction of torque with increasing speed begins earlier; this is probably due to additional throttling and heat losses with the result that fuel consumption is greater than for a standard engine without the additional chamber.

Fig. 8 shows fuel consumption and pollutant emissions of the turbulence chamber engine compared with a standard engine with ignition timing 30° or 15° respectively advanced. The turbulence chamber engine consumed more fuel. CO mass emissions differ only slightly. The NO values are similar to those reached with a standard engine when using retarded ignition. HC-emissions are increased. Maximum temperature in the combustion chamber is reduced in the turbulence chamber engine but the combustion is accelerated so that the exhaust gas temperature is lower and less HC after burning is achieved.

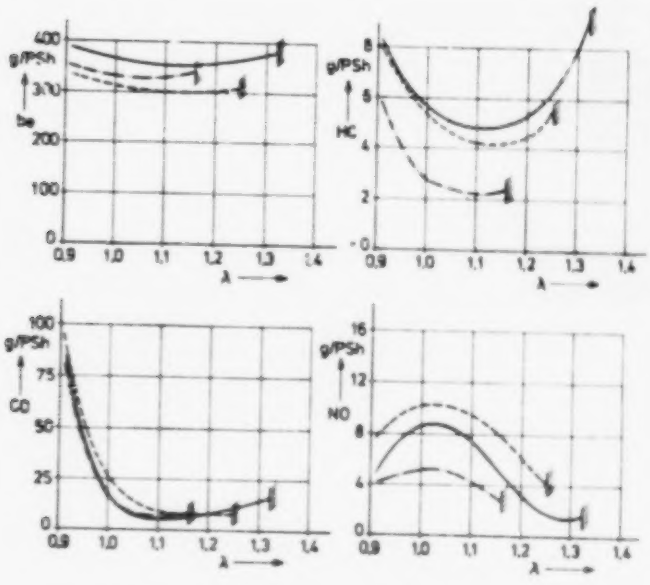

Fig. 8

Fuel consumption and pollutant emissions

—— engine with turbulence chamber, ignition point 15° BTC

-.-.- engine without turbulence chamber, ignition point 15° BTC

----- engine without turbulence chamber, ignition point 30° BTC

measured at 2000 rpm and 36 Nm

The advantage of the turbulence chamber engine is the much leaner misfire limit. By fully utilizing it a lower NO-value is obtainable compared with a standard engine.

3. NO_x-Sensor

In all attempts to simultaneously achieve low emission of exhaust gas pollutants and low fuel consumption, the reduction of the NO_x-emission is problematic. With catalytists or EGR a deterioration of the efficiency during the lifetime must be expected. Therefore, a method of checking the various decontamination systems has to be developed. The only possibility of ascertaining whether the NO_x-reduction is sufficient, in our opinion, is to monitor the NO_x-emission itself. Since it is relatively easy to convert NO electrochemically, the development of an electrochemically working NO_x sensor has been undertaken.

Fig. 9 is a schematic diagram showing the construction of the sensor. A sample volume of exhaust gas, when passing through the sensor, is diffused through a thin PTFE-diaphragm. This NO_2 then diffuses through a second PTFE-diaphragm and is reduced to NO_2^- by a catalyst electrode which is the cathode of an electrochemical cell (reaction 2).

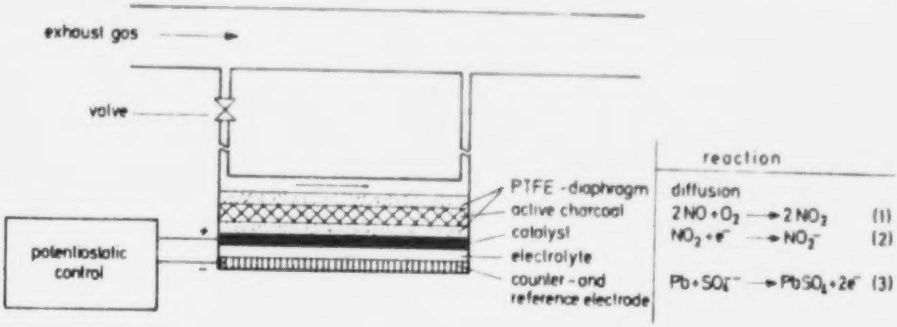
exhaust gas
valve
potentiostatic control
+
−
PTFE -diaphragm
active charcoal
catalyst
electrolyte
counter - and reference electrode
reaction
diffusion
$2NO + O_2 \rightarrow 2NO_2$ (1)
$NO_2 + e^- \rightarrow NO_2^-$ (2)
$Pb + SO_4^{--} \rightarrow PbSO_4 + 2e^-$ (3)

Fig. 9

NO_2-sensor (principle)

Dependent on the NO_2 contents the voltage/current curves shown in fig. 10 can be measured. Without load the electrode shows a potential which is only a little dependent on the NO_2 concentration. If this potential is lowered, a reduction current flows caused by the reduction of NO_2. The more negative the potential is adjusted the higher becomes the current and the more NO_2 is reduced.

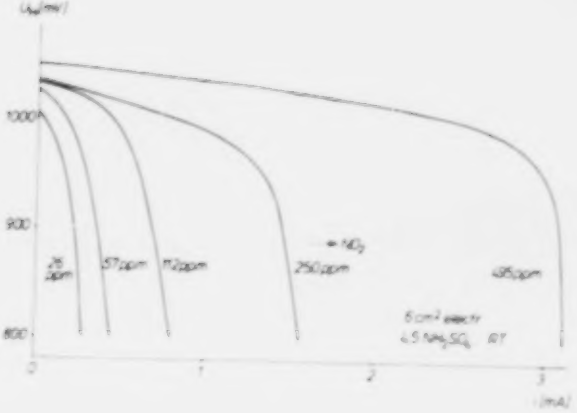

Fig. 10

Current/voltage diagram of the cathodic reduction of NO_2 for various contents of NO_2

Finally, a state is attained at which all NO_2 diffused through the diaphragm is immediately converted. The NO_2 concentration at the electrode decreases to zero so that a further reduction of potential doesn't cause a further increase of current. This "diffusion limiting current" is determined solely by the amount of NO_2 diffusing through the diaphragm: As diffusion through a diaphragm is linearly dependent on the concentration gradient at the diaphragm, Fick's first low gives a linear relationship between concentration and current J_g:

$$J_g = n\,F\,S\,D \cdot \frac{C'}{d} \quad (4)$$

The result is a diffusion limiting current directly proportional to the amount of NO_2 concentration C'.

According to this cathodic electrode reaction on the working electrode an anodic electrode process with the same current as in the cathodic process must take place on the counter electrode. In the case in question we use sulfuric acid, H_2SO_4 as an electrolyte and lead Pb as a counter electrode. In the anodic process $PbSO_4$ is formed according to the equation (3).

If the current used is not too high the potential remains sufficiently stable. The potential against hydrogen is - 300 mV and the optimum potential for NO_2 reduction is + 900 mV. A potentiostat therefore has to keep the cell voltage constant at 1200 mV.

Several NO_2 sensors have been tested successfully in the laboratory. The preceding oxidation of NO to NO_2 on the other hand is still problematic and therefore an object of further investigations.

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Symbols

λ = A/F* equivalence ratio or (excess) air factor

$= \frac{\text{actual A/F* ratio}}{\text{stoichiometric A/F* ratio}}$

A/F* = air/fuel ratio

C' = NO_2 concentration

D = diffusion coefficient

d = thickness of the diaphragm

F = Faraday number

n = number of electrons per mole NO_2

S = surface area of the electrode

J_g = diffusion limiting current

U_H = potential against H_2-electrode in the same solution

Combustion Initiation in Otto Cycle Engines

D. F. Moyer, J. R. Asik, W. G. Rado, A. H. Turner
Scientific Research Staff, Ford Motor Company,
P. O. Box 2053, Dearborn, Michigan USA

Pollution control of spark ignited gasoline engines has prompted investigations with lean mixtures and exhaust gas recirculation which make ignition difficult. Experiments in wider electrode gaps, higher spark energy, and different spark waveforms are described for a limited set of speed and torque. Improvements in emissions, fuel economy and driveability are shown.

Pollution Control needs are inexorably pushing the automotive industry to use fuel mixtures which are difficult to ignite. This is steadily leading to vehicles requiring tighter and tighter control of engine parameters to achieve barely acceptable driveability.

Considerable effort is being expended trying to find ways to improve combustion initiation in very lean mixtures and mixtures with a higher percentage of recirculated exhaust gas (EGR). It has been established by a number of workers that certain ignition system changes can be quite effective in extending lean misfire limits and improving EGR tolerance.

One of the changes which has proved to be effective is increased spark plug gap width. This approach exposes a larger volume of mixture to the spark while it also reduces the quenching effect of the electrodes on the initial flame kernel. With the exposure of a larger volume of mixture to the spark, it is felt that one improves the likelihood of combustion in a non-homogeneous mixture.

At Ford we have been exploring techniques which allow us to expose larger and larger volumes to the spark, and we hope that this approach will lead to reliable operation with A/F ratios in excess of 20:1.

We have some preliminary results with effective gaps ranging up to 0.175 inches and we plan to go beyond that in the future. Obviously, we would like to do this without resorting to excessive secondary voltages.

Some results of our investigations are now presented. First, the relationship between the ignition system and the size of the arc in the spark plug with respect to the total electrical energy dissipated in the arc and its rate of delivery will be discussed. Then, qualitative results concerning the improvement in ignition reliability, fuel economy and driveability that can be achieved using extended arc lengths will be given.

In investigating the relationship between an ignition system and the arc generated in a spark plug gap, information was acquired by recording the time traces of the arc sustaining voltage and the corresponding time variant arc current. From these traces three useful parameters were defined: the total energy delivered in the arc, the rate of energy delivery and the effective value of the arc resistance. The variation of these parameters was investigated for a breaker point ignition system as a function of gas pressure and arc length. For 1 atm gas pressure, the typical variations of the total energy dissipated in the arc and the rate of energy delivery were determined to be between 14 and 25 millijoules at a rate of between 7 and 33 watts for gaps between 0.035 and 0.175 inches. It was noted that for this particular ignition system a gap of .105" size leads to the dissipation of the maximum amount of the stored coil energy in the arc. Tests were run of the sustaining voltage and of the time variant arc current for gaps of .035" and .105" size. It was seen that the larger gap has about three times the sustaining voltage value while energy is delivered in one-half the time compared to the smaller gap. The variations of the total energy delivered in arcs as a function of gas pressure for a .035" and a .105" size gap were determined to be 20 to 26 millijoules and 27 to 54 millijoules respectively for a pressure range of 0-140 PSIG.

These data indicate that just by varying the arc length, the total energy delivered from a particular ignition system and the rate of delivery can be influenced considerably. This concept thus allows an optimization possibility that could make a more efficient use of the stored energy in the ignition system.

Utilizing the ability to vary the length of the arc generated in the spark plugs, preliminary investigations of their benefits during various engine operating conditions have been investigated.

In-car performance tests were carried out using a 1973 Pinto Station Wagon equipped with a 2000 cc engine. The performance of arcs of various size was compared in the following manner. The number one cylinder intake manifold runner of the 2000 cc engine was equipped with a valve-controlled air inlet. After the engine was stabilized in a warm idle condition, enough air was introduced to lean out the gas-fuel mixture to the point of producing misfires for about 70% of the spark plug firings using a spark plug with a specific arc length. The occurrence of misfires was monitored using an electronic combustion analyzer (Plasma Probe). Then, leaving the engine adjustments the same, another spark plug was installed with a different arc length and the percent change of spark plug firings resulting in misfires was observed. Data were accumulated checking at least 900 consecutive spark plug firings for the occurrence of misfires for each arc length. The results are shown in Table 1. The indication "thin" and "thick" corresponds to electrode sizes of

Table 1

Performance Improvement Achieved with Extended Arc Length Plugs

Type of Plug	Length of Arc (inches)	Time Sequence of Data Taken	Average Misfires
BF42 (new)	.050	1	64.8
BF42 (thin)	.050	2	58.6
Special (thin)	.150	3	38.5
BF42 (new)	.035	4	76.1
BF42 (thin)	.035	5	37.6
Special (thin)	.105	6	32.0
BF42 (new)	.020	7	76.0
BF42 (thin)	.020	8	52.8
Special (thin)	.060	9	42.0
Special (thin)	.060	10	40.0
BF42 (thin)	.020	11	55.5
BF42 (new)	.030	12	70.7
Special (thick)	.090	13	40.8
BF42 (new)	.030	14	66.7
Special (thick)	.090	15	45.3

.032" and .067" diameters, respectively. Comparing runs 9 and 10, good reproducibility from one arc length setting to the next is indicated. Comparing runs 8, 9, 10 and 11, good overall reproducibility is indicated. Both thin and thick electrode larger arc-length spark plugs showed an improvement in engine performance when compared to standard arc length plugs. This confirms the predicted improvement of increased spark volume over and above the reduced quenching inherent in thin electrodes. The possible improvement in fuel economy that could be obtained by the use of extended-arc-length spark plugs has been investigated through a 9 point mapping of a 351 CID production engine modified for fuel injection. The 9 operating points of specific engine speed and load were representative of the dominant modes of operation encountered during CVS test runs used for the certification of passenger vehicles for meeting Federal Pollution Standards. Based on such 9 point mappings, projections were made indicating the level of HC, CO, NOx emissions and a corresponding fuel economy value to be expected during a CVS test run. The results are shown in Table II.

TABLE II

TYPE OF PLUG	HC g/mile	CO g/mile	NOx g/mile	FUEL ECONOMY miles/gallon
BF42 (.035")	4.00	5.36	4.24	14.07
BF42 thin (.035")	2.96	3.50	5.19	14.34
Special (.105")	3.68	4.93	5.20	14.78

As can be seen from these data, the spark environment control allows tradeoffs between emissions and fuel economy.

Finally, a preliminary evaluation of the effect of extended arc lengths on driveability were made and it was found that for engines with tight emission calibrations, driveability is improved at idle and part throttle accelerations at all speeds with the extended spark length.

If some way could be found to electrically extend the spark volume and perhaps even control this volume, these beneficial results should be further enhanced.

Another of the ignition changes which has been investigated is a change in the waveshape of the spark current and voltage. To study new waveshapes, we have developed a unique Ferroresonant Capacitor Discharge Ignition (FCDI) System. The specifications for the FCDI system are given in Table III. The high peak secondary voltage capability (45 kv/50 pf) enables it to be used with wide gaps. The ignition capacitor is charged and discharged more than once during the combustion initiation of one cylinder. We have called this multiple firing a restriking capability. FCDI also has the capability of sustaining the spark continuously between each CD firing. This sustaining power level can be varied between 0 and 100 watts. The total spark duration, consisting of the initial firing, refirings, and sustaining, can be adjusted between 0.3 and 12 ms. Thus, it is possible to program the spark energy over a wide range from 160 to more than 1600 millijoules. FCDI combines many of the advantages of the basic CD ignition system and the basic inductive ignition system without some of their attendant disadvantages.

TABLE III

SPECIFICATIONS FOR FCDI SYSTEM

Breakdown Voltage Risetime - 1 microsecond
Spark Duration - 0.3 to 12 ms
Restriking Rate - 0.3 to 3.0 kHz
Peak Secondary Voltage into 50 pf - 45 kV
Sustaining Power Level - 0 to 100 watts

The FCDI system was first compared to a conventional inductive ignition on a single cylinder laboratory engine. The engine was run at 1500 rpm while the A/F ratio, load, and EGR percentage were varied. The FCDI system was operated at a 5 ms (45 degrees crank angle) duration and at a 3 kHz restriking rate and maximum sustaining power. The inductive ignition possessed a 40 millijoule input energy and a 1.5 to 2.0 ms nominal spark duration.

The results showed that both lean misfire limit and EGR tolerance are extended with the FCDI system. The amount of extension varies with engine load, being largest at the lighter loads studied. Engine power and emissions at non-misfiring conditions are the same with both ignition systems.

The details of this work are given in the SAE paper No. 740188 by Harrington, Shishu, and Asik.

The FCDI system was next operated at a marginal operating point of a 460 CID V8 engine. The engine speed was 1000 rpm, A/F ratio was 17.1, EGR was 0, SA (BTC) was 55 degrees (MBT) for FCDI and 37 degrees (MBT) for conventional. At that operating point, the level of sustaining power between the CD restrikes was varied between 0 and 100 watts. Even though the spark sustaining power was reduced to zero, residual ignition energy in the form of multiple CD firings was present. A total of four (4) CD firings at a spacing of 1.5 ms were used.

The results showed a marked dependence of the various engine parameters on the level of sustaining power. In particular, the brake specific nitrogen oxide (BSNO) and torque show an increase of 100% and 25% respectively as the sustaining power was increased, while the brake specific fuel consumption (BSFC) and the brake specific carbon monoxide (BSCO) decreased about 25%. The brake specific hydrocarbon (BSHC) appear relatively insensitive to sustaining power. We also note the presence of a plateau above 50 watts where the indicated parameters level off. In comparison, the production ignition produced 6 times the hydrocarbons while using 30% more fuel for the same torque.

Multiple pressure vs. crank angle indicator diagrams for these same engine operating points were taken. The brake specific emissions in gms/hp-hr and fuel consumptions in lbs/hp-hr are shown in Table IV.

TABLE IV

	BSHC	BSCO	BSNO	BSFC
Conventional -37 SA	19.6	6.9	2.5	1.00
FCDI - 37 SA	2.8	5.8	2.4	0.83
FCDI - 60 SA	2.5	5.1	7.3	0.74

There were several misfires found which gave an indication of the motoring curve. There was a wide spread in the pressure levels showing cyclic variation for the conventional ignition. Changing to the FCDI results in no misfire and much greater consistency in the pressure curve. Since the fuel preparation was by ordinary carburetion, one might expect considerable variation in the homogeneity of the mixture. The long spark duration (about 40 crank angle degrees was shown on the trace) of the FCDI causes a higher probability of combustion due to the larger sample of gas exposed to the spark during the longer time period. The conventional spark, although starting at the same time, lasts only 12 degrees to 15 degrees. Although the peak torque did not increase, the higher average results in a 20% improvement. When the spark timing is advanced, the peak pressures increase and occur closer to top center. The cyclic variation, however, increases and a significant percentage of pressure traces fall in the range of those generated with 37 degrees spark angle. One might conclude from these traces that the ability to run the engine at optimum efficiency is ignition limited under these operating conditions.

A further study has been made of the ignition timing effects on HC, ignition delay and combustion period. Two similar operating points were used and the FCDI sustaining current was continuous over 45 degrees of crank angle. No EGR was used, the air/fuel ratio was 15.6/1 and standard plugs with a 0.035 inch gap were used. It was found that at 1000 rpm and 50 ft-lbs the FCD ignition system permits a greater spark advance (by 25 degrees) before the HC begins to rise - indicating poor combustion. However, the brake specific fuel consumption (BSFC) has already been minimized at 35 degrees and the spark advance is not very useful for this operating condition. The same effect was found for 1200 RPM and 100 ft. lbs.

The ignition delay is defined as the elapsed crank angle between the spark initiation and a pressure rise above the motoring curve. This delay increases to 55 degrees at -75 degrees SA with increasing spark timing advance for FCDI at the lighter load. The conventional system becomes unstable around

-40 degrees SA probably because its spark does not persist long enough to insure combustion as the piston compresses the mixture to a more favorable initiation condition.

The combustion period is defined as the elapsed crank angle between combustion initiation (the end of the ignition delay period) and the inflection point of the decreasing pressure curve. It was found that there is little difference at the lower speed/load point (although considerable instability) but at the higher point the FCDI period continues to decrease with spark advance up to 75 degrees. Although the ignition delay increases with increasing spark advance, the combustion period continues to decrease. There is some possibility that the very early spark can start a kernel of combustion which will not propagate until the piston increases the pressure and temperature to the point that propagation begins. Light loads, lean mixtures, and large amounts of EGR coupled with heterogeneous fuel/air mixture distributions with normal carburetion and manifolding combine to produce cyclic variations in the combustion process. More spark energy appears to reduce these variations.

We have seen from this preliminary information some effects of increased spark length, increased spark duration and increased spark energy. Our investigations have not proceeded to the point where we can be definitive about these effects. Better control of the ignition, however, would seem to be very desirable for two principal reasons:

1. A more complete combustion process within the cylinder may be possible, leading to reduced emissions.

2. Extension of engine stable operations into currently unstable areas may benefit the necessary fuel economy/emission control trade-offs. If for instance, it was possible to operate the engine very lean (an A/F in excess of 20:1) NOx and CO control might be possible without a catalyst if the HC could be controlled.

Finally, I would like to comment on the possibility of a more efficient transfer of electrical energy and chemical energy. We have in some instances injected more than a joule of electrical energy and passed the point of diminishing returns for combustion benefits. It would seem that there must be a better way to make the electrical/ chemical energy transfer and reduce the electrical energy required.

In view of the worldwide pressures to conserve our portable fuels and reduce the air pollution contributed by vehicles, a continuation and expansion of the work described in this paper seems appropriate. I would urge those of you conducting similar investigations to redouble your efforts and invite others with appropriate resources to join in. Thank you for the opportunity of participating in this conference.

Catalytic post-combustion of the exhaust gases of Otto cycle engines with controlled admixture of secondary air.

G.R. HAERTEL Ing. (grad.)
Deutsche Vergaser GmbH & Co. KG
4040 Neuss, Leuschstr. 1

Carbon monoxide, hydrocarbons and nitric oxide may be removed from the exhaust gases of engines(Otto cycle)simultaneously in only one catalyser bed, if the gases are kept stoichiometric within very close limits The continual measuring of the oxygen contents upstream the catalyser permits the exact adaptation of the admixture of secondary air by a feed back control system. The engine operation with a mixture slightly leaner than stoichiometric permits a good driveability assuring at the same time a good utilisation of fuel.

Des gaz d´échappement de moteurs à combustion interne (Otto) peuvent en même temps être purifiés dans un seul lit catalysateur d´oxyde de carbone, de hydrocarbure et d´oxyde d´azote lorsque, dans des limites très restreintes, la composition des gaz d´échappement est maintenue stoichiométrique. Le mesurage continu de la teneur en oxygène en amont du catalysateur permet une adaptation parfaite de l´admission de l´air secondaire par l´intermédiaire d´un circuit feed back. La marche du moteur avec un mélange se trouvant tout juste sous les limites stoichiométriques assure une bonne conduite et une exploitation encore satisfaisante du carburant.

Abgase von Ottomotoren können gleichzeitig in nur einem Katalysatorbett von Kohlenmonoxid, Kohlenwasserstoffen und Stickoxid gereinigt werden, wenn innerhalb sehr enger Grenzen die Zusammensetzung des Abgases stöchiometrisch gehalten wird. Die fortlaufende Messung des Sauerstoffgehaltes vor dem Katalysator gestattet eine genaue Anpassung der Zufuhr von Sekundärluft über einen Regelkreis. Der Motorbetrieb mit knapp unterstöchiometrischem Gemisch gewährleistet gute Fahrbarkeit bei noch guter Kraftstoffausnutzung.

Introduction:

In order to comply with the stringent legal requirements covering the permissible emissions of carbon monoxide (CO), unburnt hydrocarbons (HC), and nitric oxides (NO_x), as they were originally scheduled e.g. to be valid in the USA for vehicles of model year 1976 onwards and which with similar values will also be effective for the model year 1978 or somewhat later, the exhaust gases of a conventional internal combustion engine (Otto cycle) have to be subjected to a post-combustion. If, in addition to those for CO and HC, also the limits for NO_x are very low, there would be the problem that during post-combustion a reducing atmosphere would be required to lower the NO emissions while an oxidizing atmosphere would be needed to lower the CO and HC emissions. It was proved that beside the conventional two-bed-procedure the two processes will also be performed in only one catalyser bed if a stoichiometric composition of the exhaust gases is maintained (1).

Although at first sight it appears to be the safest way for the exhaust gas post-combustion to clearly separate reduction and oxidation, the post-combustion with a stoichiometric composition of the exhaust gases in only one bed offers several advantages:

1. Earlier begin of reduction and oxidation after cold starting, as only one catalyser has to be warmed up

2. smaller space requirement for the post-combustion system

3. lower cost

4. no formation of ammonia (NH_3)

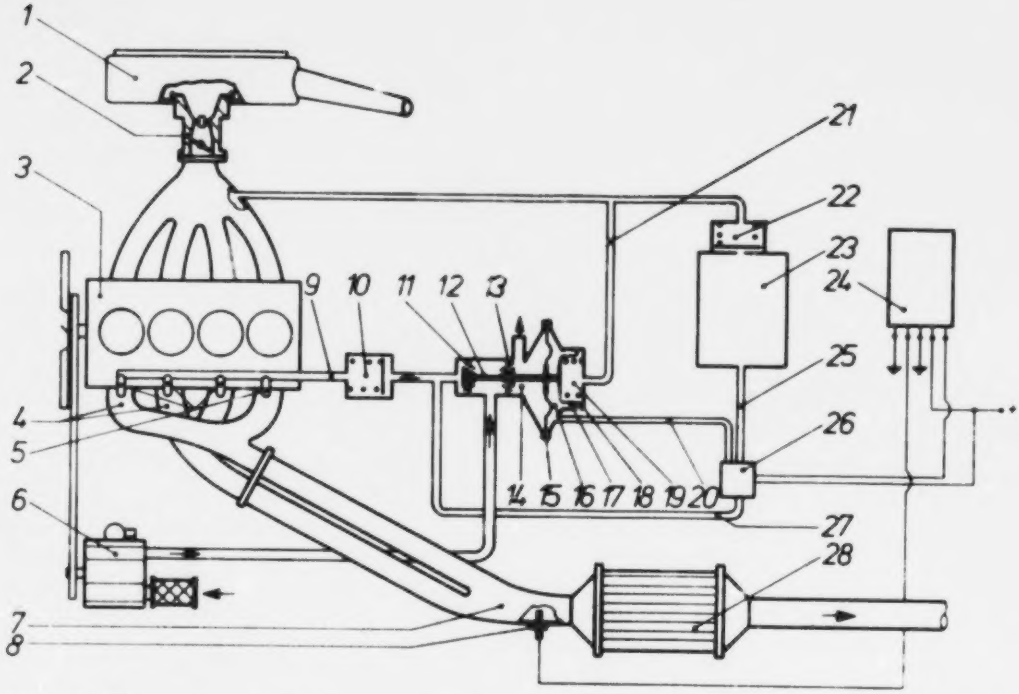
Disadvantages are:

1. In the catalyser a stoichiometric mixture ratio must be maintained within very close limits.
2. The catalyser must comply with particular requirements.

In order to obtain good conversion rates of carbon monoxide, unburnt hydrocarbons, and nitric oxide, the permissible deviation from the stoichiometric mixture in the catalyser is according to the required rate of conversion extremely small and will, in any case, still be below ± 0,5 %. This range, the so-called λ^*-range, is by no means obtainable by precise setting of a carburetter or an injection system. Effects as variable ambient conditions, instationary operation and tolerances in series production of the engine and the fuel metering elements lead to exceeding the permissible range of the mixture ratio. Therefore, the composition of the exhaust gases conducted to the catalyser has to be measured continually so that the mixture is controlled either downstream or upstream the engine to get the stoichiometric mixture. As tests have shown, in principle, fuel as well as air can be used upstream or downstream the engine as control factors. In publications so far, two solutions (2) (3) were presented and further developed almost to mass production maturity.

Design and operation of the system with controlled admixture of secondary air

Fig. 1 shows schematically according to the latest state of development, the components of the feed back system and the Otto cycle engine. The carburetter 2 meters fuel into the air aspirated by the engine via the air cleaner 1 so that the engine 3 receives an intake mixture with a deficiency of air of 0-10 %. The exhaust gases formed by the combustion in the engine flow through the exhaust manifold 4 and the exhaust pipe 7 into the catalyser 28. Preferably, by means of individual injector tubes 5, at all times sufficient secondary air is admixed to the exhaust gas flow so that the catalyser 28 will receive a stoichiometric mixture after the exhaust streams of the individual cylinders have been mixed. The secondary air is metered by the secondary air control valve 14 by means of the control sections 11 and 13. The quantity of secondary air supplied in linear dependency of the engine rpm is distributed to the control sections 11 and 13 according to the position of the valve rod 12. The air quantity metered by the control section 11 is conducted via the air line 9 and the non-return valve 10 into the exhaust gas stream, while the air quantity flowing past the control section 13 is blown off. The valve rod 12 is firmly attached to the diaphragms 15 and 17 so that the forces acting on these diaphragms directly position the valve rod. If ambient pressure acts in the diaphragm chamber 16 it will be possible to obtain a metered quantity of secondary air which is independent from engine rpm and approximately proportional to the quantity of intake air



1 air cleaner
2 carburetter
3 engine
4 exhaust manifold
5 individual injector tubes
6 secondary air pump
7 exhaust pipe
8 sensor
9 air inlet pipe
10 non return valve
11 control section of injected air
12 valve rod
13 control section, outlet air
14 control valve for secondary air
15 diaphragm
16 diaphragm chamber
17 diaphragm
18 spring
19 diaphragm chamber
20 alternating pressure pipe
21 manifold depression pipe
22 non return valve
23 depression reservoir
24 electronic control unit
25 depression reservoir pipe
26 electromagnetic three way valve
27 injection pressure pipe
28 catalyser

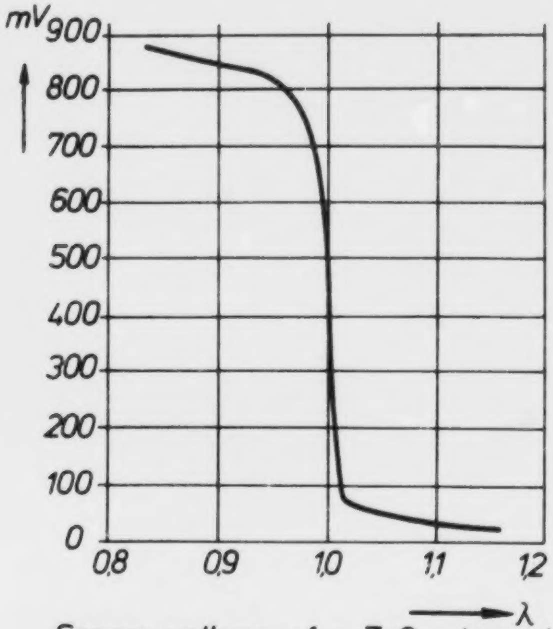
Otto engine equipped for catalytic post combustion
and controlled admixture of secondary air

Fig. 1

by subjecting diaphragm chamber 19 via pipe 21 to the intake manifold pressure and suitable design of the spring 18. By variable exhaust back pressure this relation may be disturbed.

If, however, the diameter of the diaphragm 15 is chosen so that the differential face to diaphragm 17 is in a certain relation to the characteristics of the spring 18 and the diaphragm chamber 16 is subjected with the variable injection pressure via pipes 20 and 27, an adaption of the control sections 11 and 13 to the prevailing exhaust back pressure is possible. In this context it may be noted that the total section of the individual sections 11 and 13 is relatively large and about constant with the stroke so that the supply pressure as well as the power requirement of the secondary air pump can be kept small. With increasing exhaust back pressure the supply pressure of the secondary air pump only increases sufficiently to maintain the quantity of the flow to be metered.

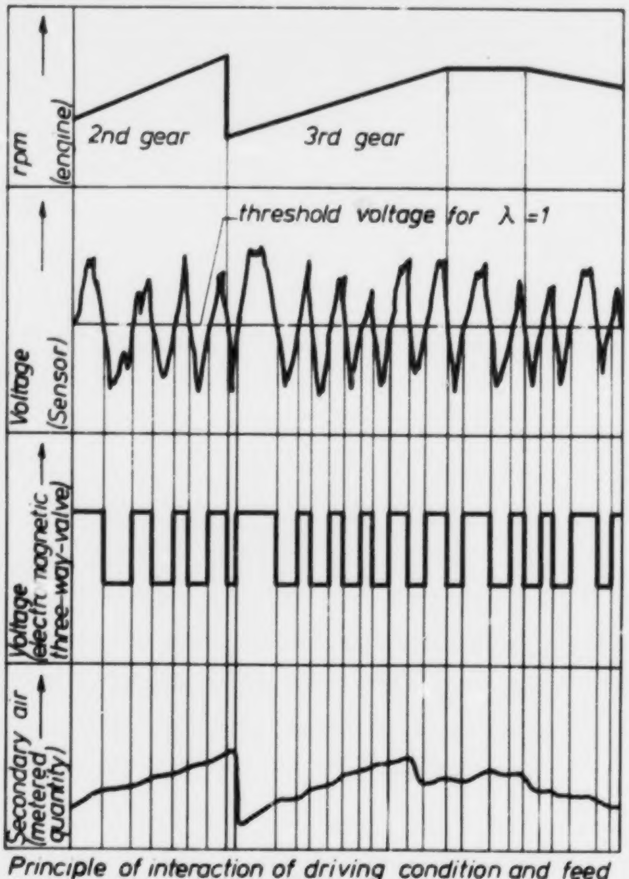
If by means of the selection of air pump size e.g. 20% secondary air is metered in relation to the quantity of air aspirated by the engine there will be 15% excess air in the catalyser with a deficiency of air of 5% during the combustion in the engine. If the diaphragm chamber 16 is connected by means of the pipes 20 and 25 with the vacuum reservoir 23 which is subjected to the intake manifold pressure of the engine via a non-return valve 22, the valve rod 12 is moved into the direction of smaller valve sections 11. The quantity of secondary air metered to the exhaust flow will hereby be increasingly reduced. By alternatively switching the diaphragm chamber 16 for different durations by means of the electromagnetic three-way-valve 26 to the effective pressure lines 25 and 27 any desired pressure between the two effective pressures may be maintained in the diaphragm chamber and the rate of metering of secondary air may be varied between 0-2o%. If the composition of the gases upstream the catalyser is continually measured by means of a sensor 8 and according to signals $\lambda >$ or < 1 the effective pressure line 25 or 27 is connected with the diaphragm chamber 16 by means of the electronic control unit 24 and the three-way-valve 26, it is possible to adapt the quantity of the secondary air to the prevailing exhaust gas composition with fast switching operations so that the necessary stoichiometric mixture ratio in the catalyser can be kept within very close tolerances. As sensor for the determination of the exhaust gas composition within the range of the stoichiometric mixture the ZrO_2-sensor described by Zechnall and Baumann (2) for measuring the net-oxygen contents in the exhaust gas stream may be used.



Sensor voltage of a ZrO_2-element versus air ratio λ

Fig. 2 Curve of the sensor signal as function of the air ratio. For stoichiometric mixture the sensor signal is very steep in the range of 300 to 400 mV. If the electronic control unit is subjected to a threshold voltage of this value the sensor voltage can serve directly as criterion of the exhaust gas composition $\lambda >$ or < 1 and the three-way-valve can be controlled via a power amplifier.

Fig. 3 shows a typical curve of the sensor voltage during instationary operation, the control voltage of the three-way-valve, and the quantity of air metered by the secondary air control valve.



Principle of interaction of driving condition and feed back control units as voltage of sensor, control of three-way-valve and metered secondary air.

If the vehicle is accelerated, as may be seen on the curve engine rpm versus time, the quantity of the secondary air is adapted to the increasing quantity of exhaust gas owing to the also changing speed of the secondary air pump and the changing manifold depression. This basic characteristics of the quantity of secondary air is superimposed by a precision control on the basis of the instantaneous exhaust composition. The value of sensor voltage which is higher or lower than the threshold voltage controls the position of the three-way-valve and herewith the quantity of the secondary air. The fast variations of the engine rpm and the manifold depression when changing gear also lead to sudden changes of the quantity of secondary air.

In order to maintain small amplitudes of the quantity control of secondary air, in principle, a feed back system with small dead times should be given preference. This may be achieved by locating the injection of secondary air and the sensor as close together as possible. By means of throttle jets in the effective pressure lines the setting speed of the secondary air control valve has to be adapted to the dead times of the feed back system and to other influencing factors as width of variation of the air ratio of the intake mixture during instationary operation.

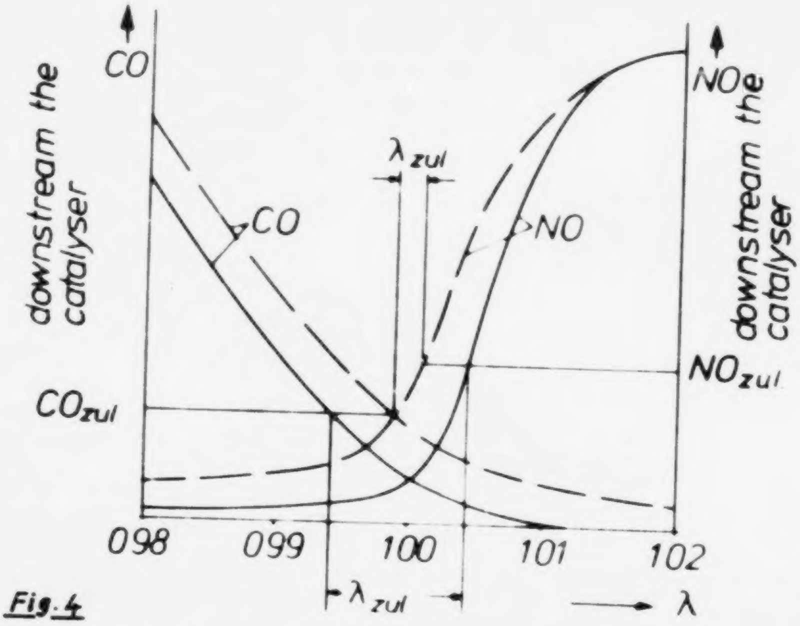


Fig.4

Influence of catalyser activity on the permissible width of the λ-range of new ———— and aged – – – – – catalysers

Fig. 4 shows that according to the efficiency of the catalyser the range of λ in which the permissible limits of CO and NO are complied with will differ. With increasing conversion rate for CO and NO the permissible width of the range is rapidly reduced and may even be negative. Here, negative will mean that also with a theoretical control width of $\lambda_{zul} = 0$ the test can no longer be passed. As the unburnt hydrocarbons react clearly better than e.g. CO they do not require such a width of the λ - range. The concentration for CO and NO stated as permissible downstream the catalyser greatly depends on the emission in the starting and warming-up phases of the engine in addition to the permissible test limits in g/mile or g/test. Under unfavourable conditions in these operating phases the permissible limits for the total tests may be reached or exceeded already before the catalytic post-combustion is initiated. In order to warm up the catalyser to operating temperatures as rapidly as possible after starting fŏr the oxidation at 250 - 300 °C it is amongst others of advantage to meter the secondary air to obtain excess air of 15 % (4). In the system described this may be achieved by a voltage signal of the electronic control unit to the three-wy-valve by which the effective pressure line 27 (injection pressure) is continually connected with the secondary air control valve. After initiation of the oxidation the catalyser quickly further warms up to reach 350 - 400 °C so that with simultaneous warming-up of the sensor to at least 400 °C the feed back system begins to operate reducing the secondary air quantity to get a stoichiometric air ratio in the catalyser. From that time onwards the oxidation and the reduction are performed in the catalyser simultaneously.

Results:

The equipment of various vehicle models with a catalyser and the described secondary air control system has shown that with adaptation of the composition of the aspirated mixture, the ignition advance, and the exhaust gas recirculation the values for all three components clearly fall below the original emission limits for 1976 when fresh catalysers are used. As the intake mixture had to be kept slightly below $\lambda = 1$ there will in general be no problems concerning the driveability in spite of the exhaust gas recirculation. For the warming-up phase of the engine, however, certain adaptations are desirable.

Further development operations are in progress.

The fuel consumption only slightly increased when compared to an engine controlled to $\lambda = 1$ on the intake side. Comparative measurements in the CVS test pointed to an increase of consumption of 1 - 2 % with a secondary air control system. Outside the test range influences affecting the fuel consumption inherent to the design of the system may be eliminated. When compared with a carburetter the intake mixture of which has been adjusted to optimise the consumption ($\lambda \geqq 1$) there is, however, an increase of 3 - 5 %. It is, however, only possible to exploit wholly or partly this more favourable setting of the carburetter, if the legislation does not require extremely low NO_x emissions. With relaxed requirements, it will be increasingly possible to do without the reduction of NO in the catalyser and operate the engine so that the combustion is assured with $\lambda \geqq 1$.

The durability tests of the entire feed back system on the engine test bed showed that there were no problems affecting the valves and the electronic control unit. It could even be proved that the sensor to measure the O_2 content of the exhaust gases when operated in the described control system had a durability of more than 400 operating hours with changing loads and speeds.

It became, however, clear that the catalyser still remains the critical point. The activity of the catalyser is greatly reduced with increasing operating time. It has not even been possible to provide reliable indication as to the durability. Influences like operating conditions, fuel quantity, mechanical and thermic load lead to a more or less rapid inactivation. Excessive heating e.g. by ignition misfire or excessive mechanical strain result in a rapid destruction of the catalyser. Fully suitable control and protective devices are not yet available. It is possible to increase the time during which the catalyser has sufficient activity by greater dimensions or replacements of the catalysers. This is, however, also a question of the ratio cost/benefit. Even though, in the meantime, also here substantial progress has been made, it will only be possible to comply with the extremely stringent requirements of the legislation if catalysers with great reliability and high conversion rates for the three groups of pollutants CO, HC and NO in the range of the stoichiometric mixture will be available.

$$^{*}\lambda = \text{air ratio} = \frac{\text{actual A/F ratio}}{\text{stoichiometric A/F ratio}}$$

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The Concept of the CVCC Engine System

HIDEO SUGIURA
Managing Director
Honda Motor Co., Ltd.
No. 27-8, 6-chome, Jingumae
Shibuya-ku, Tokyo, 150 Japan

We have developed a low-pollution engine, which we call the CVCC engine system. This paper describes an outline of our basic thinking in developing this system, and its structure, combustion process and performance characteristics.

PREFACE

The 1970 amendments to the Clean Air Act by the United States Congress established a major target for the automobile industry throughout the world for solving the air pollution problem arising from exhaust emissions.

Various means have been under study by automobile manufacturers in many countries for reducing unwanted emissions, such as after-burners, thermal reactors and oxidizing catalysts to control carbon monoxide (CO) and unburned hydrocarbons (HC), and exhaust gas recirculation and reduction catalysts to control oxides of nitrogen (NOx).

Most of these methods, however, are meant to give after-treatment to the gases after they are emitted from engines, and, therefore, far from assuring constant reduction of emissions due to such unsolved problems as durability and reliability of the after-treatment devices as well as generation of high temperatures therein.

We have followed the philosophy of reducing the unwanted emissions within the engine system itself as the fundamental requirement for achieving a clean engine. It is on the basis of this philosophy that we have developed what we call the CVCC engine system, wherein the combustion mechanism different from that of the conventional engine makes it possible to reduce the pollutants within the system itself through a new combustion process.

BASIC THINKING

As shown in Fig. 1, a conventional engine operates most smoothly when the weight ratio of air and fuel is on the rich side of the stoichiometric ratio (15 to 1 in case of gasoline), while it would not operate when the ratio is leaner, because of misfiring problem.

The starting point in our developing the CVCC engine system was a strong motivation to reduce unwanted emissions through an alternative engine system based on something different from conventional systems. In view of the characteristics shown in Fig. 1, the use of the "lean mixture zone" by

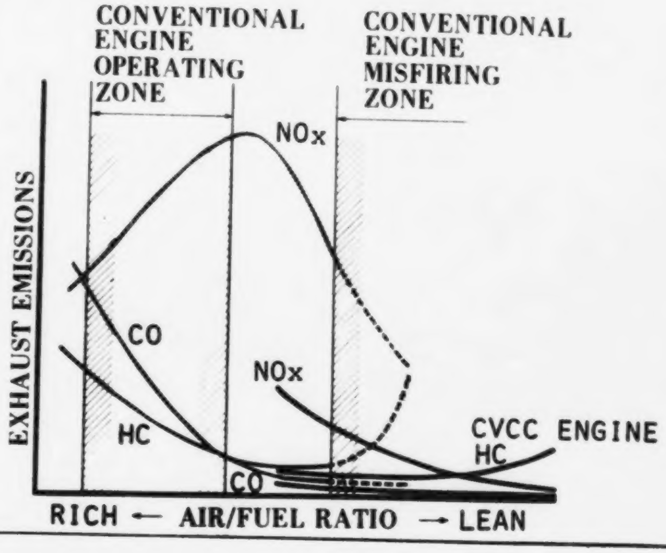


Fig. 1 Emission Characteristics vs. Air-Fuel Ratio

solving the misfiring problem was quite attractive as a means of minimizing the all three pollutants of CO, HC and NOx simultaneously.

When the "lean mixture approach" is adopted, the combustion starts with abundant oxygen, and even after the combustion process has progressed, the burned gases are well mixed with air. After leaving the exhaust ports, let alone within the combustion chambers, there occurs sufficient oxidizing reaction, making the gases almost harmless at the end of the exhaust pipe without relying on after-treatment devices such as catalytic converters.

As shown in Fig. 1, there is a close relationship between the emission of harmful gases and the air-fuel mixture ratio. In reducing the exhaust emissions, therefore, the method of supplying the fuel is one of the decisive factors.

Honda's CVCC engine system utilizes the commonly used carburetor as a means of supplying the air-fuel mixture from outside the cylinder. With the rapid progress made in the carburetor technology especially since pollution became a major issue, it would be no exaggeration to say that, at least today, the carburetor is the most suitable means of supplying fuel to the CVCC engine system. This is because, with the carburetor, techniques accumulated in the past can be fully utilized with respect to (1) the way to induce the mixture, (2) positioning of the spark plug, (3) the state of the mixture immediately before the ignition, and (4) specifications of the ignition system. Furthermore, conventional engine technology can be utilized for starting and warming up the engine.

While low emission levels must be achieved, it is absolutely essential that an automobile engine has sufficient power characteristics, and it is desirable that good fuel economy be maintained. To reduce emissions without sacrifice in fuel economy, or, if possible, by improving it, was another basic philosophy in our developing the CVCC engine system.

Lowering of the emission levels of pollutants, especially NOx, tends to result in at least some deterioration in fuel economy characteristics. A three-valve stratified charge engine system was originally invented for the purpose of improving fuel economy. We thought, therefore, that if a low-emission engine is pursued with this system, the result would be a combination of low emission levels and fuel economy comparable to or better than that of a conventional engine. The result has been that the CVCC engine system achieves the two goals of reducing emissions and improving fuel economy.

It is desirable for automobiles to be as service-free as possible. This is true of developing a low-pollution engine, which should not have more expensive replacement components. It has been for these reasons that we have avoided the use of catalytic converters in our program to develop a low-pollution engine system.

In summary, the CVCC engine system operates on an air-fuel mixture ratio totally different from that of conventional engines, achieves a clean combustion process within the system itself, and is a viable alternative engine system with outstanding fuel economy and driveability.

PREREQUISITES FOR CVCC DEVELOPMENT

Combating the automobile exhaust emission problem is a task facing all car manufacturers throughout the world. A solution to this problem can be reached only when the manufacturers adopt workable low-pollution system, and start supplying low-emission vehicles in large quantities and in a manner readily acceptable to the general public. For this reason, we have made the following conditions prerequisite to developing a low-pollution engine system.

1. The system must be such that the all three pollutants of CO, HC and NOx can be minimized simultaneously within the engine itself.
2. No major penalty in fuel economy must be associated with the system, and, if possible, improvement must be sought.
3. The system must be least dependent on technologies that have not been proven to be completely free from safety problems and secondary pollution.
4. The existing production and maintenance systems, including both hardware and software, must be utilized; and the engines must be mass-producible at reasonable cost.
5. The system must be applicable to all sizes of engine, both large and small.

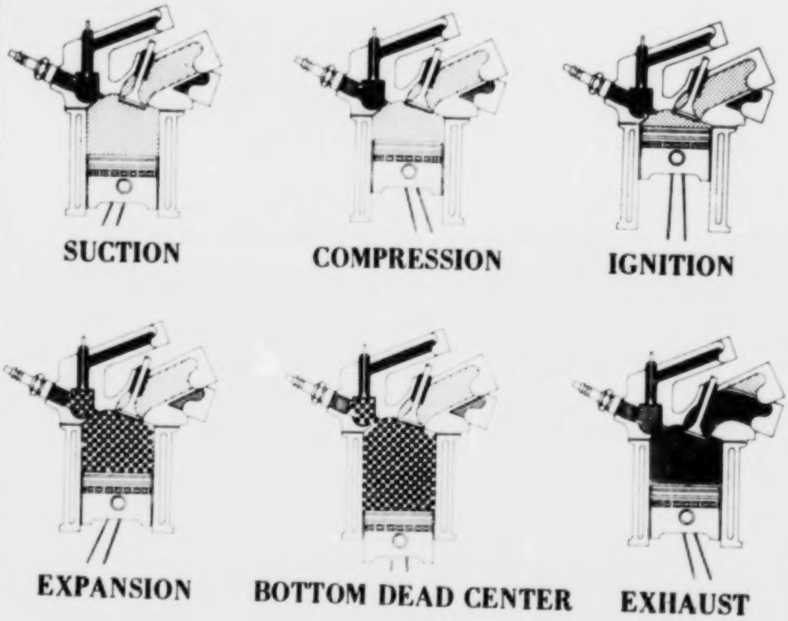
COMBUSTION PROCESS OF CVCC ENGINE SYSTEM

Following is a brief description of the combustion process of the CVCC engine system. (See Fig. 2.)

During the suction stroke, a large amount of lean mixture is supplied to the main combustion chamber, and a small amount of rich mixture to the auxiliary combustion chamber, making the overall mixture ratio lean. The amount and quality of mixtures are maintained at optimum levels from idling to full load.

Formed at the end of the compression stroke is a stratification of (1) a rich mixture around the spark plug at the auxiliary chamber, (2) a moderate mixture near the torch opening in the main chamber, and (3) a lean mixture in the remainder of the main chamber. This stratification and lack of strong turbulence in the main chamber are prerequisite to achieving the ensuing slow combustion, which is one of the features of the CVCC engine system.

Fig. 2 Combustion Process of CVCC Engine System



The rich mixture in the auxiliary chamber is readily ignited by the spark plug. The burning gas ignited in the auxiliary chamber ignites the moderate mixture near the torch opening in the main chamber, and the flame is further propagated to the lean mixture.

The peak temperature in the main chamber is low compared with the conventional engine. This serves to minimize the formation of NOx, which occurs at a very high temperature. The low CO level is a natural result of the lean overall mixture ratio. As the average temperature is kept relatively high for a long duration of time in the oxygen-rich atmosphere, unburned hydrocarbons are oxidized sufficiently, minimizing the HC emission.

CHARACTERISTICS OF CVCC ENGINE SYSTEM

While in any system there is always room for improvement, we have achieved the following with our CVCC engine system.

1. Emission Characteristics

Table 1 shows the exhaust emission levels of various CVCC engines tested by the LA-4 mode Federal Test Procedures of the United States. All these data are sufficiently low to comply with the emission standards originally set forth for 1975 under the United States Clean Air Act, even when slippage, deviation and deterioration factors are taken into consideration.

Table 1

Exhaust Emissions & Fuel Economy Measured under LA-4 Mode

Vehicle Type (transmission)	Type	Displacement (cm^3)	Exhaust Emissions (gr/mile)			Fuel Economy (mile/gal)
			CO	HC	NOx	
HONDA CIVIC	CVCC	1,488	2.42	0.24	1.39	25.5
(manual)	CVCC	1,950	2.12	0.18	0.89	22.1
Avg. '74 model 2,000 lbs cars		-	-	-	-	24.4
GM Vega	Original	2,295	10.6	2.13	3.80	17.2
(manual)	CVCC	2,295	2.62	0.26	1.16	18.9
Chevrolet Impala	Original	5,736	19.33	1.56	2.42	10.5
(automatic)	CVCC	5,736	2.88	0.27	1.72	10.5
Avg. '74 model 5,000 lbs cars		-	-	-	-	9.4

2. Fuel Economy

Also shown in Table 1 are fuel economy characteristics of CVCC engines. It is generally regarded as an extremely difficult task to reduce not only CO and HC but also NOx simultaneously without sacrifice in fuel economy, because an attempt to lower the peak combustion temperature for controlling NOx formation would inevitably lead to poorer thermal efficiency. But, we have been able to solve this problem in our CVCC engine system through a proper combination of the "lean mixture approach" with the three-valve stratified charge engine concept.

3. Performance Characteristics

Table 2 compares the power characteristics of conventional and CVCC engines. As these data show, the conversion to the CVCC system does not necessarily result in a power loss, and, indeed, in certain cases it has served to increase power.

It should be pointed out, however, that with the growing importance of the low-pollution characteristics being attached to the automobile engine, the horsepower to displacement ratio begins to become of secondary importance.

Table 2

Performance of CVCC Engines (SAE net)

Vehicle Type	Engine Displacement (cm^3)	Max Horsepower /Engine Rev.
HONDA CIVIC	1,950	70 ps/5,000 rpm
GM Vega Original	2,295	72 ps/4,500 rpm
GM Vega CVCC	2,295	73 ps/4,500 rpm
Chevrolet Impala		
Original	5,736	160 ps/4,000 rpm
CVCC	5,736	160 ps/4,000 rpm

Today, therefore, what are important of an engine are: low emission levels, compact size, light weight, good fuel economy, small vibration and noise, adequate driveability, and good durability and reliability.

STRUCTURE AND MANUFACTURING PROCESS

The CVCC engine system is constructed in such a way that production technologies accumulated and refined over the past decades can be fully utilized.

Fig. 3 General Cutaway View of a CVCC Engine

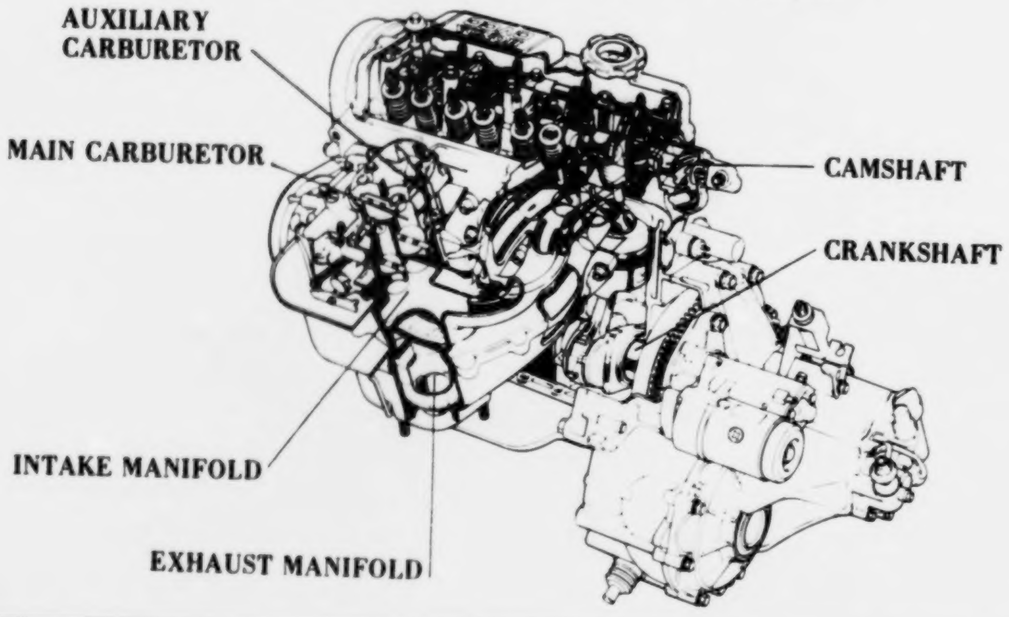
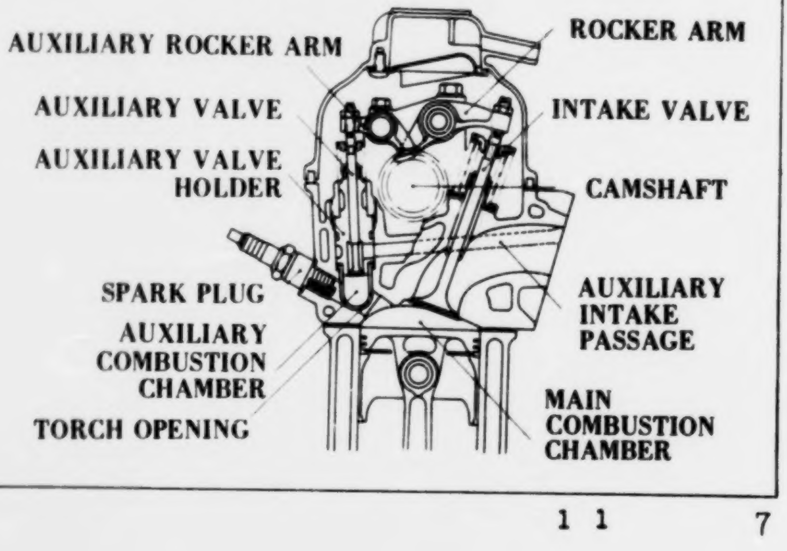


Fig. 3 is a general cutaway view of a CVCC engine, which differs from a conventional engine only in its cylinder head, camshaft, carburetor and the manifolds.

1. Cylinder Head

A cutaway view of a CVCC engine cylinder head is shown in Fig. 4. It has a large main combustion chamber and a small auxiliary combustion chamber, which are connected by a torch opening. The main

Fig. 4 Cutaway View of a CVCC Cylinder Head



chambers has the main intake valve and the exhaust valve, while the auxiliary chamber is fitted with an auxiliary intake valve and the spark plug.

2. Manifolds

The intake and exhaust manifolds are of one-unit construction, so that the intake charges are pre-heated by the exhaust gas temperature for vaporization. This serves to raise the air-fuel mixture temperature quickly after starting, shorten the warming-up period, and effectively reduce exhaust emissions at cold starting.

3. Carburetor

The basic structure of the CVCC carburetor is similar to conventional one. We have added separate venturis and float chambers for the main and auxiliary combustion chambers. It has a primary and secondary venturis to supply a lean mixture to the main chamber, and an auxiliary carburetor to supply a rich mixture to the auxiliary chamber. The throttle valves for the main and auxiliary chambers are linked in such a way as to maintain certain relations between their openings, so that the emission levels, driveability and fuel economy are kept optimum under all load conditions.

4. Production Process

A major portion of the machining processes are common to both conventional and CVCC engines. The only difference in machining the cylinder head, for example, is three stages added to the CVCC engine for machining of the auxiliary combustion chamber.

EVALUATION OF THE CVCC ENGINE SYSTEM

The CVCC engine system has been evaluated quite highly by many quarters. In December, 1972, the United States Environmental Protection Agency tested three Honda CVCC vehicles (one of which had completed a 50,000-mile durability test), and reported in February, 1973:

1. All three Honda CVCC vehicles repeatedly met the emission levels originally required for 1975 under the Clean Air Act.
2. There does not appear to be a significant fuel economy or driveability penalty associated with the engine.
3. There is no aldehyde emission problem associated with the CVCC engine.
4. There is no particulate emission or smoke problem associated with the CVCC engine.
5. The CVCC engine achieved lower levels than any other gasoline fueled engine without after-treatment ever tested by the Environ-

mental Protection Agency.

In September, 1973, a Chevrolet Impala car, whose 350 CID V-8 engine had been converted to the CVCC system, was tested by EPA, which later reported:

1. The ability of the CVCC engine concept to meet the original statutory 1975/76 hydrocarbon and carbon monoxide standards when applied to a full-sized vehicle application was confirmed.
2. Fuel economy of this vehicle was comparable to or slightly better than 1973 vehicles having similar weight and engine.

In February, 1973, meanwhile, the National Academy of Sciences said in its report to the U.S. Congress and EPA that the Honda system is the most developed stratified charge engine to date, and had the lowest bare-engine emissions.

Thus, both the Environmental Protection Agency and the National Academy of Sciences regard the CVCC engine system highly for being capable of meeting the original emission standards for 1975 under the U.S. Clean Air Act without such after-treatment devices as EGR and catalytic converters. They also point out that this system is the quickest to be translated into mass-production.

Since December, 1973, we have already been marketing the Honda Civic CVCC model in Japan, which meet the Japanese 1975 emission standards that are identical to the original standards set for 1975 in the United States. Similar type cars will soon be introduced in the United States as the 1975 model.

We are currently in the stage of receiving the final evaluation of our CVCC engine system from the purchasing public on the market place, and we have every confidence that the public reaction will be favorable.

CONCLUSION

Summing up, the low-pollution CVCC engine system we have developed has the following major characteristics:

1. It is capable of meeting the original statutory 1975 emission standards for the United States and those required for 1975 in Japan without such after-treatment devices as catalytic converters, without sacrifice in fuel economy and driveability, and without a risk of causing secondary pollution.
2. Minimal modifications are required in converting the existing production facilities to the CVCC engine system, because the only major differences between this system and the conven-

tional engine are in the cylinder head, carburetor and manifolds.

3. Since the existing technologies can be fully utilized in the CVCC engine system, transfer of our technology is easy, and its products have outstanding reliability and durability.

Note: For further technical details of the CVCC engine system, see SAE Papers Nos. 740605 and 741158.

Über Untersuchungen von VW-Schichtladungskonzepten*)

Dr. techn. W. BRANDSTETTER
Dipl. Ing. G. DECKER
Dr. Ing. H.A. KUCK
Ing. grad. K. REICHEL
Forschung 2, VOLKSWAGENWERK AG
3180 WOLFSBURG

Summary

Experimental results from watercooled single-cylinder stratified charge engines with a subdivided combustion chamber and for two principles, the scavenged and unscavenged prechamber, are reported. The development of the third generation 1.6 l aircooled opposed type cylinder engine with its mechanical fuel injection system is described and engine maps are discussed. The results with the VW 1303-Beetle indicate very low NO$_x$ - and CO-emissions with fuel economy not impaired. Engine power output and vehicle acceleration are equal with those of the production engine in the same vehicle.

Résumé:

Présentation des études expérimentales relatives aux moteurs monocylindriques à charge stratifiée, refroidis par eau, munis d'une chambre de combustion subdivisée, la préchambre étant balayée ou non. Description du développement de la troisième génération des moteurs avec cylindres opposés, ayant une cylindrée de 1600 cm^3, munis d'une système d'injection méchanique et discussion de leurs charactéristiques. Mesurages sur la VW 1303-Coccinelle montrent, que le taux des polluants NO$_x$ et CO est très peu élevé. Néanmoins la puissance maximale du moteur et la capacité d'accélération atteignent aux véhicules de série.

Zusammenfassung

Es wird berichtet über Versuche an wassergekühlten Einzylindermotoren mit Ladungsschichtung im geteilten Brennraum für zwei Verfahren, nämlich der gespülten und ungespülten Vorkammer. Die Entwicklung der dritten Generation des 1.6-l luftgekühlten Schichtladungsmotors mit einem mechanischen Kraftstoffeinspritzsystem wird beschrieben und einige Motorkennfelder werden diskutiert. Messungen am VW 1303-Käfer ergaben sehr niedrige Stickoxyd- und CO-Emissionen ohne Verbrauchsanstieg. Die maximale Leistung des serienmäßigen Ottomotors und auch das Beschleunigungsverhalten des Serienfahrzeugs wurden erreicht.

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*) Gefördert vom Bundesminister für Forschung und Technologie

1. EINLEITUNG

Hauptzielsetzung ist die Erfüllung der ab 1977 vorgesehenen US-Emissionswerte und der für die Bundesrepublik Deutschland für 1980 geplanten Abgasvorschriften im wesentlichen durch innermotorische Maßnahmen, also unter Vermeidung von katalytischen Nachbehandlungsvorrichtungen. Dabei soll kein Kraftstoffmehrverbrauch und kein wesentlicher Leistungsverlust gegenüber dem konventionellen Otto-Motor auftreten. Ferner müssen die Gesamtkosten des Konzeptes unter denen von anderen Alternativen liegen. Ein wichtiger Vorteil gegenüber dem noch unbefriedigenden Nachlassen der Konvertierung im Katalysator wird auch in der annähernden Konstanz der Emissionen über der Laufstrecke gesehen.

Eine von der Fa. Eaton durchgeführte Studie (1) kam zu dem Ergebnis, daß die Verwendung von Katalysatoren nur eine vorübergehende Lösung darstellt und der Marktanteil von Schichtladungsmotoren in den kommenden Jahren stark zunehmen wird. Beispielsweise wird der Honda Civic mit CVCC-Schichtladungsmotor (2) in Japan bereits seit 1974 serienmäßig gebaut und 1975 auch nach USA exportiert.

Für die Entwicklung eines so neuartigen Verbrennungsverfahrens sind Grundlagenversuche unumgänglich. Einzylindervoruntersuchungen hatten Vorteile bei Ladungsschichtung im unterteilten Brennraum ergeben. Diese zunächst am luftgekühlten Einzylindermotor durchgeführten Untersuchungen, die für die Klärung prinzipieller Zusammenhänge noch weitergeführt werden, resultierten in der Erstellung von mehreren 1,6 l-Vierzylinderversuchsmotoren und Konzeptfahrzeugen (1303-VW-Käfer). Aufbauend auf diese Erfahrungen ist das Verbrennungsverfahren auf wassergekühlte Motoren übertragen worden. Hier werden grundlegende Zusammenhänge an zwei Verfahren, nämlich der Schichtladung mit ungespülter Nebenkammer und Benzineinspritzung, sowie der Schichtladung mit gespülter Nebenkammer und Vergaser als Gemischbildner, untersucht.

2. UNTERSUCHUNGEN AM EINZYLINDERPRÜFSTAND

2.1. Luftgekühlter PCI[x]-Motor

Über die Ergebnisse von eigenen Grundlagenversuchen am luftgekühlten Einzylindermotor bei Schichtladungsbetrieb war wiederholt ausführlich berichtet worden (3 - 6). Ähnliche Untersuchungen wurden von K. Klöcker durchgeführt (7). Auch hier stand die Optimierung der Brennraumgeometrie im Vordergrund.

Auf die zuletzt verwendete Bauform wird bei der Konzeptbeschreibung des Vierzylindermotors näher eingegangen. Während sich bisher eine relativ späte Einspritzung in die Vorkammer und eine sehr kleine Kraftstoffmenge im Verlauf der Optimierungsarbeiten ergab, werden nun neue kostengünstigere Möglichkeiten untersucht.

Hierbei wird angestrebt, eine größere - im Extremfall die gesamte Kraftstoffmenge - schon während des Saughubes in die Vorkammer einzubringen, wobei ein Teil in den Hauptbrennraum überströmt und das magere Grundgemisch bildet. Durch eine längere Aufbereitungszeit sowie durch Verwendung von Isolierschalen zur Erhöhung der Vorkammerwandtemperatur wird die Gemischaufbereitung verbessert.

2.2. Wassergekühlter PCI-Motor

Für die Untersuchung neu erstellter Zylinderköpfe für wassergekühlte Schichtladungsmotoren mit ungespülter Vorkammer standen zunächst Vorkammerausführungen mit einem Kammervolumen von 21 % bzw. 28 %, jeweils bezogen auf das Kompressionsvolumen zur Verfügung. Die Versuche wurden bei einem konstant gehaltenen Verdichtungsverhältnis von 8,1 durchgeführt.

Neben der Ermittlung günstiger Einstellgrößen bei gegebener Brennraumkonfiguration standen verschiedene Variationen bezüglich Kolben, Düsen- und Kerzenlage sowie der Schußkanalgeometrie im Vordergrund.

Bei einem Kompromiß bezüglich der drei Schadstoffkomponenten und des Kraftstoffverbrauchs haben sich im Teillastgebiet Vorkammerkraftstoffmengen von 10 - 25 % der Gesamtkraftstoffmenge als günstig erwiesen. Dabei sind im allgemeinen bei Optimierung der Einflußparameter Zündung und Drosselklappe den kleinen Vorkammerkraftstoffmengen niedrige CO-Werte sowie gute Verbräuche bei schlechteren NO_x-Werten zugeordnet. In Bild 1 sind beispielhaft die Abhängigkeiten der spezifischen Emissionen und des Verbrauchs vom Kraftstoffmengenverhältnis Vorkammermenge zu Gesamtmenge $m_{B,VK}/m_B$ dargestellt. Die berechnete Luftzahl in Vorkammer und Hauptbrennraum zum Zündzeitpunkt sind im Bild unter Berücksichtigung des Restgaseinflusses zusätzlich aufgetragen. Im Bild 1 wird deutlich, daß sich unter den angegebenen Randbedingungen bei einem Vorkammermengenanteil von ca. 20 % ein guter Kompromiß ergibt. Bei Senkung des Vorkammeranteils auf ca. 10 % ist zwar eine erhebliche CO-Absenkung und eine geringfügige Verbrauchsverbesserung zu beobachten, allerdings steigen die Kohlenwasserstoff- und besonders die Stickoxidemissionen stark an. Eine Steigerung der Vorkammermenge auf ca. 30 % hat einen Anstieg aller drei Emissionskomponenten und des Kraftstoffverbrauchs zur Folge. Bei einer Gesamtluftzahl von 1,1 und einem Luftverhältnis von ca. 0,45 in der Vorkammer, bzw. von 1,55 im Hauptbrennraum ist die CO-Produktion in der Vorkammer so groß, daß bei der anschließenden Nachverbrennung im Hauptbrennraum wegen mangelhafter Vermischung mit der an sich vorhandenen Überschußluft eine ausreichende Nachoxidation unterbleibt.

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[x] Pre-Chamber-Injection

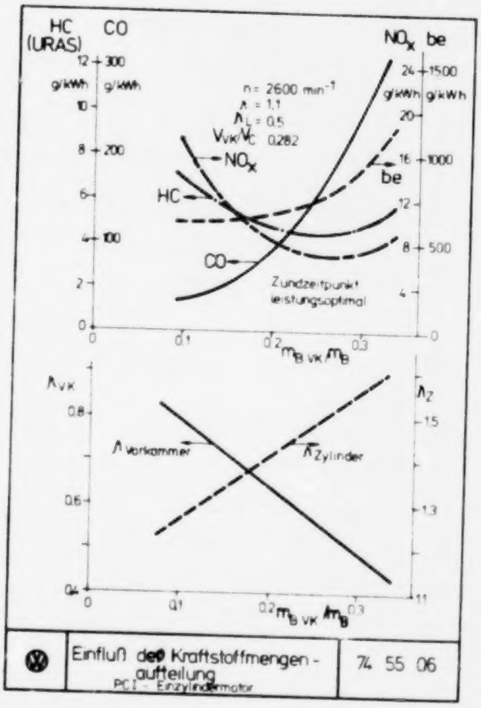
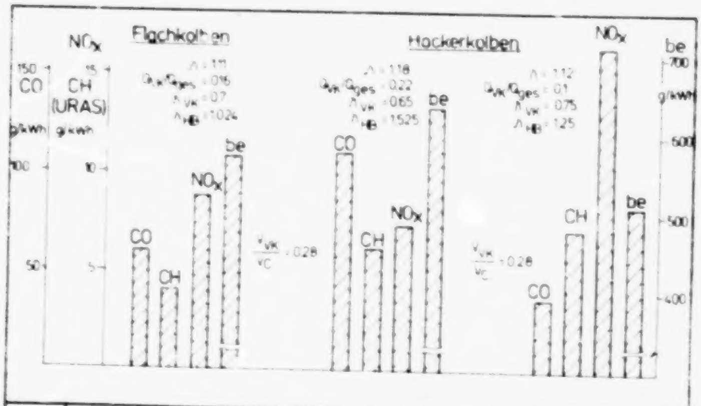


Bild 1

Aus den Versuchen hat sich ergeben, daß die Vorkammergröße keinen markanten Einfluß auf die erzielbaren Emissionen hat. Vielmehr konnten hinsichtlich HC und CO wegen der günstigeren Brennraumgestaltung mit einem Flachkolben gegenüber dem ursprünglich verwendeten "Höckerkolben" Fortschritte erzielt werden, Bild 2.



Einfluß der Brennraumgeometrie
PC1 Einzylindermotor
74 55 08

Bild 2

2.3. Wassergekühlter 3-Ventil Motor

An einem wassergekühlten Einzylindermotor wurde ein Zylinderkopf mit einem Vorkammeranteil von 14 % bei einer Verdichtung von 8,35 untersucht. In dieser Ausführung mit gespülter Vorkammer wurde ein fettes Teilgemisch über ein in der Vorkammer sitzendes kleines Einlaßventil eingebracht. Wegen der mageren Überschiebemenge während der Verdichtung ist ein stark überfettetes Gemisch mit einer Luftzahl von beispielsweise 0,3 erforderlich, das zur Vermeidung von Kraftstoffkondensation stark vorgewärmt werden muß. Für die ersten Prüfstandsuntersuchungen wurde zur Reduzierung der unabhängigen Einstellparameter die Hilfsgemischtemperatur mit 100°C konstant gehalten.

Die im Bild 3 dargestellten Abhängigkeiten gelten für n = 2600 1/min und p_{me} = 1,4 bar, bei konstanter Gesamtluftzahl und konstantem Gemischmassenverhältnis. Es zeigt sich, daß mit steigendem Verbrennungsluftverhältnis des Hilfsvergasers der Kraftstoffverbrauch und die CO-Emission absinken, andererseits die NO_x- und HC-Emissionen steigende Tendenz haben. Zur Interpretationserleichterung sind im unteren Bildteil die unter Annahme verschiedener Vereinfachungen berechneten Vorkammerverbrennungsluftverhältnisse aufgetragen. Offensichtlich werden bei dieser Brennraumkonfiguration für nahezu gleiches Luftverhältnis in Vorkammer und Hauptbrennraum im Bereich von $\lambda \approx 1$ niedrige CO- und Verbrauchswerte und hohe Stickoxidemissionen erreicht. Bei stärkerer Ausnutzung des Schichtladungseffektes steigen Verbrauch und die Kohlenmonoxidemission, verbunden mit fallenden NO_x-Emissionen, an. Hier muß durch Brennraummodifikationen die Nachverbrennung im Hauptbrennraum verbessert werden.

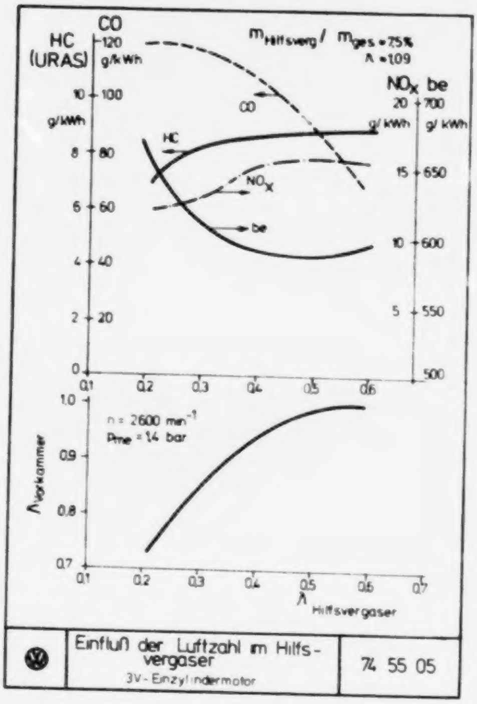


Bild 3

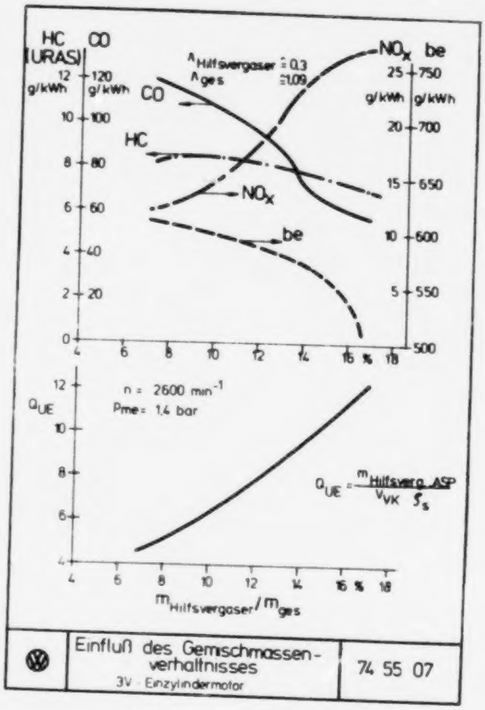


Bild 4

Der ausgeprägte Abfall der HC-Emission bei sehr fetten Hilfsvergasergemischen muß durch die höheren Brennraumtemperaturen bei Verschleppung der Verbrennung erklärt werden.

Neben dem Kraftstoffluftverhältnis am Nebenkammervergaser kommt andererseits auch dem Massenverhältnis von Nebenmenge und Gesamtmenge eine gewisse Bedeutung zu. Ein Maß für die beim Saugtakt von der Vorkammer in den Hauptbrennraum überströmende fette Gemischmasse ist die Überströmkennzahl, die insbesondere die Größe des Gemischbereichs charakterisiert, der zwischen dem fetten Vorkammergemisch und dem mageren Hauptgemisch im Bereich des Überströmkanals vorhanden ist. Wie aus Bild 4 ersichtlich, steigen bei konstantem Luftverhältnis am Nebenvergaser und konstantem Gesamtluftverhältnis die NO$_x$-Emissionen mit wachsender Nebenmenge, d.h. größerem Übergangsbereich bezüglich der Gemischqualität zwischen Vorkammer und Hauptbrennraum, an, während Verbrauch und die CO-Emission offensichtlich aufgrund eines besseren Durchbrennverhaltens abfallen. Die HC-Emission bleibt im wesentlichen unbeeinflußt.

3. DRITTE GENERATION DES LUFTGEKÜHLTEN 1.6 L PCI-MOTORS

3.1. Konzeptbeschreibung

Ausgehend vom luftgekühlten 1,6 l Ottomotor des VW 1303 Käfers, entstand ein Schichtladungsmotor mit Einspritzung einer Teilkraftstoffmenge direkt in die Vorkammer bzw. in das Saugrohr und einer Brennraumform wie sie in Bild 5 gezeigt ist. Das Volumen der kugelförmigen Vorkammer beträgt etwa 20 % des Kompressionsvolumens. Überströmkanalgröße und -lage sind nach den Gesichtspunkten "weicher" Verbrennungsablauf, geringer Drall in der Vorkammer und niedrige Bauteiletemperaturen aufbauend auf Einzylinderergebnisse gestaltet.

Im Gegensatz zum Motor der Generation 1, der noch ohne Ansaugluftdrosselung arbeitete, sind bei der Generation 2 und 3 eine Drosselklappe vor dem Saugrohrverteiler installiert. Der in der Generation 1 auftretende hohe Luftüberschuß bei Teillast wurde verringert, um eine günstigere HC-Emission zu erhalten.

Am Motor selbst betreffen wesentliche Änderungen nur den Zylinderkopf. Gegenüber dem Serienmotor wurde der Vergaser durch ein Einspritzaggregat der Fa. Schäfer Einspritztechnik GmbH, München, ersetzt. Bei dieser Sonderausführung einer mechanischen Einspritzpumpe, die auf serienmäßigen Teilen aufbaut, wird in die Vorkammer ca. 70 Grad vor OT mit einem Abspritzdruck von 35 bar eingespritzt, während die Hauptkraftstoffmenge wie üblich in die Ansaugkanäle eingespritzt wird.

Zur Vereinfachung des Systems sind bei dem Vierzylinder-Motor die Einspritzdüsen für die Hauptkraftstoffmenge in zwei Gruppen zusammengefaßt. Die Abspritzmengen der Vorkammerdüsen liegen zwischen 1,5 bis 2,5 mm^3/Hub. Bei dem Motor der Generation 3 wird die Vorkammer mit einer last- und drehzahlunabhängigigen Einspritzmenge versorgt. Probleme bereitet die Beherrschung der kleinen Vorkammerabspritzmengen.

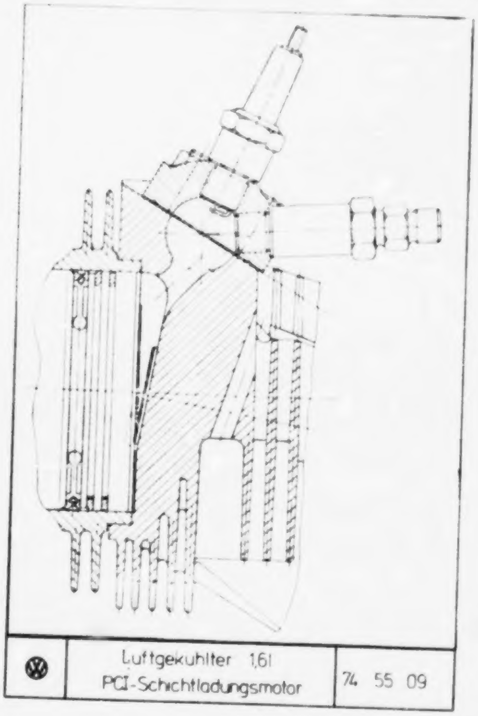


Bild 5

Verbesserungen zur exakten und tropfenfreien Dosierung konnten erst nach zahlreichen Versuchen und Änderungen an Pumpe und Ventilen erreicht werden.

Ein sicherer Kaltstart wird durch Einspritzen von Kraftstoff durch eine Zentraldüse im Saugrohrverteiler erreicht. Hier bietet sich die Möglichkeit einer exakten Anpassung an den Zusatzbedarf, also auch einer Warmlaufanreicherung. Für das Versuchsstadium wurde eine elektronische Steuereinrichtung entwickelt, die intermittierend und motortemperaturabhängig, durch Wärmefühler gesteuert, über ein elektromagnetisches Kaltstartventil arbeitet. Die Anreicherungsmenge kann im Leerlaufbereich bei kaltem Motor das Drei- bis Vierfache der normalen Einspritzmenge betragen. Auf eine vollständige Kraftstoffabschaltung im Schiebebetrieb wurde verzichtet, da u.a. beim Wiederzuschalten der Kraftstoffzufuhr durch die Brennraumabkühlung hohe HC-Emissionen auftreten. Lediglich bei Drehzahlen über 3000 1/min erfolgte eine Abschaltung der Hauptbrennraummenge mit Rücksicht auf Fahrverhalten und Kraftstoffverbrauch. Um bei den darunterliegenden Drehzahlen ein Durchbrennen des Gemisches zu ermöglichen, wird ein unterdruckgesteuertes Schubluftventil zur Zufuhr der notwendigen Zusatzluft zugeschaltet.

3.2. Versuche am Motorprüfstand

Die Motoren der Generation 3 wurden zunächst stationär vermessen und die Einstellgrößen optimiert. Dabei wurden die Abstimmung des Zünd- und Einspritzzeitpunktes und des Kraftstoff-Luftverhältnisses im Hinblick auf geringe Schadstoffemissionen und geringen Verbrauch bei gutem Laufverhalten durchgeführt.

Die maximale Leistung des Schichtladungsmotors beträgt 50 DIN-PS (37 kW) bei 4000 1/min, gegenüber dem US-Serienmotor mit 48 PS. Das maximale Drehmoment liegt um ca. 3 % unter dem des Serienmotors, der Verlauf der Drehmomentkurve ist jedoch flacher. Der minimale Verbrauch in Höhe von 224 g/PSh liegt wenig unterhalb der Vollastlinie bei 2000 1/min, der minimale Verbrauch des obengenannten Serienmotors beträgt 223 g/PSh bei 2500 1/min ebenfalls in der Nähe der Vollastlinie.

Die Darstellung der Gesamtluftzahl im Mitteldruck/Drehzahl-Kennfeld (Bild 6) zeigt, daß mit Ausnahme des Vollastbereiches der stöchiometrische Wert immer überschritten wird. Im Teillastbereich sogar bis zu rund 35 %. Damit ist bei einem konventionellen Otto-

PCI-Schichtladungsmotor
luftgekühlt, 1,6 l

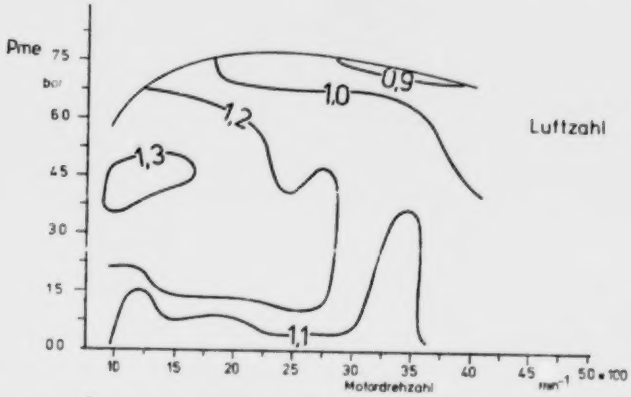


Bild 6

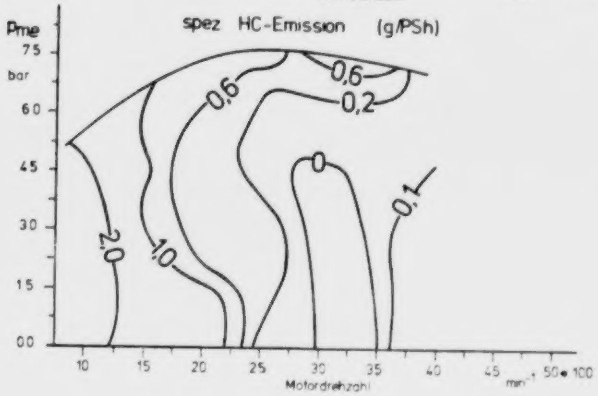


Bild 7

motor die Zündgrenze weit überschritten. Durch einen gedehnten Verbrennungsablauf ist der Einfluß auf die Abgastemperatur geringer als diese hohen Luftzahlen erwarten lassen. Die HC-Emissionen zeigen in weiten Teilen des Kennfeldes, insbesondere im Teillastgebiet bei Drehzahlen über 2500 1/min, sehr niedrige Werte (Bild 7). Einer weiteren Verbesserung bedarf insbesondere der niedrige Drehzahl-Lastbereich, einschließlich des Leerlaufes. Ein wesentlicher Fortschritt wurde in den CO-Emissionen der Motorgeneration 3 gegenüber dem Schichtladungsmotor der Generation 2 erreicht. Im Betriebsbereich des CVS-Tests wurden die Emissionen um ca. 75 % abgesenkt, aufgrund der Anfettung entlang der Vollastlinie sind dort die CO-Werte entsprechend hoch (Bild 8). Die NO_x-Emissionen des Schichtladungsmotors mit ungespülter Vorkammer liegen sehr niedrig im Vergleich zu einem konventionellen Ottomotor, sie sind im Mittel um etwa 70 % reduziert, Bild 9. Die Verstellung des Zündzeitpunktes über Drehzahl und Last beträgt ca. 25°KW und ist damit wesentlich geringer als beim konventionellen Motor.

Eine ausführlichere Kennfelddarstellung ist in (8) gegeben.

PCI-Schichtladungsmotor
luftgekühlt, 1,6 l

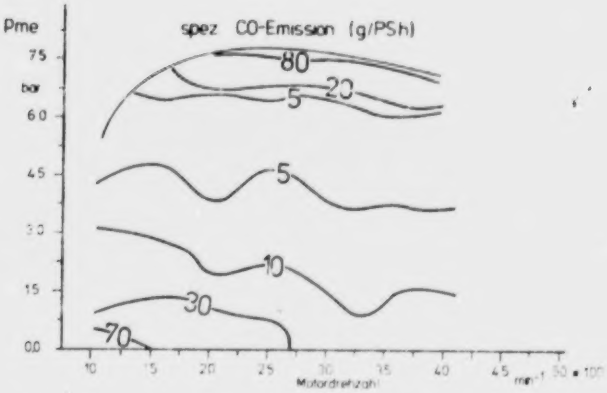


Bild 8

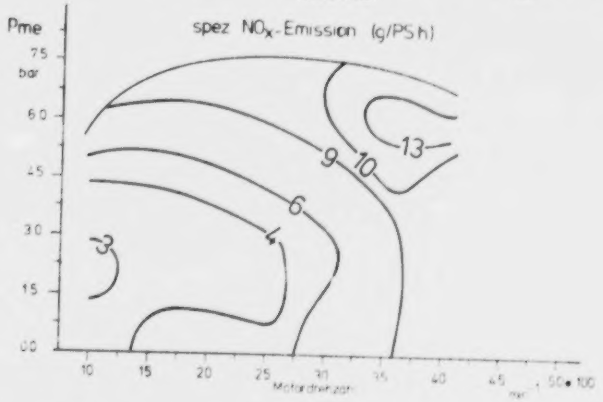


Bild 9

3.3. Versuche am Rollenprüfstand

In zahlreichen Rollentests nach dem CVS'75 Verfahren und dem EFZ wurden Motoren der 3. Generation im VW-Käfer getestet. Im Verlauf dieser Testreihen erfolgte die Anpassung der auf dem Prüfstand ermittelten Abstimmung an den instationären Fahrbetrieb. Problematisch hinsichtlich der Emissionen sind vor allem die Start- und Warmlaufphase sowie der Schubbetrieb des Motors. Hier ist eine besonders exakte Abstimmung erforderlich.

Mit diesen Motoren wurden im CVS'75 Test folgende Rohemissionen gemessen (Schwungmasse 1020 kg, d.s. 2250 lbs):

HC	1,9	-	3,0	g/M
CO	4,4	-	8	g/M
NO_x	0,75	-	0,80	g/M

Für Messungen nach dem Europa-Zyklus ergaben sich folgende Werte (Schwungmasse 907 kg, d.s. 2000 lbs):

HC	4	-	8	g/Test
CO	20	-	30	g/Test
NO	1,4	-	1,7	g/Test.

Die im Hinblick auf die Zielsetzung noch unbefriedigenden HC-Emissionen erfordern noch weitere Optimierungsarbeiten. Das HC-Kennfeld, Bild 7, läßt niedrigere Werte im Fahrzyklus erwarten. Dies weist daraufhin, daß insbesondere die instationäre Abstimmung noch verbessert werden muß. Die Verwendung von Vorkammereinsätzen und eine Änderung des Auspuffsystems nach dem Prinzip des mageren Reaktors sind zwei darüber hinausgehende, erfolgversprechende Maßnahmen.
Das Fahrverhalten sowie das Motorengeräusch unterscheiden sich nicht von dem des serienmäßigen Fahrzeuges. Auch bei Messung der Beschleunigung (0 - 100 km/h) erreichte das PCI-Fahrzeug mit 20,8 s die Werte des Serienfahrzeugs (20,5 s). Es besteht keine Ruß- und Geruchbelästigung.

3.4. Verbrauch und Oktanzahlbedarf

Unter Alltagsfahrbedingungen, bei scharfer Fahrweise und Kurzstreckenverkehr betrug der Straßenverbrauch rd. 9,7 l/100 km. Die Normverbrauchsmessung nach DIN 70030 ergab 9,6 l/100 km gegenüber 9,2 bis 9,6 l/100 km am US-Serienfahrzeug. Der günstige Verbrauch in Relation zu den niedrigen Stickoxidemissionen ist hier besonders hervorzuheben.
Bei der Ermittlung des Oktanzahlbedarfs[x] zeigte sich, daß bei der derzeitigen Abstimmung dieser im unteren Drehzahlbereich dem des Serienmotors entspricht. Positiv erscheint der deutliche Abfall mit zunehmender Drehzahl, weil damit keine Gefahr mehr für Hochdrehzahlklopfen besteht.

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[x] Die Messungen wurden mit Unterstützung der Dt. Shell AG, Hamburg, durchgeführt.

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Verbrennungsablauf und Abgasemission in einem Motor mit dem Porsche-Schichtlade-Kammer-System.

Lange, Karlheinz, Dr.-Ing.
Gruden, Dušan, Dr.-Ing.
Dr.-Ing.h.c.F.Porsche AG., Entwicklungszentrum Weissach
7251 Weissach

Low exhaust emission standards of motor vehicle engines lead to refinement of the conventional piston engine and to occupation with alternative powerplants.
As for the present it is not likely to use any special powerplant in great number, Porsche started basic research work on a stratified charged engine.
This paper reports of the parameters on combustion and exhaust emission of the SKS engine.
Moreover the possibility of operating the stratified-charged-engine with methanol is examined.

Les réglementations sur l'émission des gaz d'échappement des vehicules á moteur conduit au dévèloppement du moteur Otto et à l'éxamen des systemes de propulsion alternatif.
A l'heure actuelle il est impossible d'utiliser en serie ces systèmes de propulsion. C'est pourquoi Porsche a étudié les dévèloppement de base d'un moteur á charge stratifié.
Cet exposé fait état des diveres influences sur la combustion et l'émission de gaz d'echappement du moteur SKS.
En outre on a étudié les possibilités de faire marcher le moteur a charge stratifié au methanol.

Die Reglementierungen der Abgasemission von Fahrzeugmotoren führten zu einer Weiterentwicklung des Ottomotors und zur Beschäftigung mit alternativen Antriebssystemen.
Da vorläufig keine Chance für die Verwendung von Sonderantrieben in größeren Serien besteht, wurde bei Porsche die Grundlagenentwicklung eines Schichtlademotors betrieben.
In dieser Arbeit wird über die Einflußgrößen, auf Verbrennungsablauf und Abgasemission des SKS-Motors berichtet.
Außerdem werden die Möglichkeiten geprüft, den Schichtlademotor mit Methanol zu betreiben.

1. Einleitung

Die Festlegung gesetzlicher Grenzwerte für die Emission verschiedener Abgasbestände und die Suche nach einem wirtschaftlichen Fahrzeugantrieb führten zu einer intensiven Weiterentwicklung des Ottomotors und zur Beschäftigung mit den verschiedensten alternativen Antriebssystemen. Da zumindest für die nächsten Jahre keine Chance für die Verwendung von Sonderantrieben in größeren Serien besteht, wurde bei Porsche die Erforschung und Grundlagenentwicklung eines Schichtlademotors betrieben.

Von den zwei grundsätzlich unterschiedlichen Möglichkeiten, eine Schichtung der Ladung zu verwirklichen, wurde beim Porsche-SKS-Motor die Lösung mit einem geteilten Brennraum gewählt, da die Ausführungen mit offenen, ungeteilten Brennräumen eine Empfindlichkeit auf Drehzahl- und Laständerungen aufweisen.

Ausgehend von den einzelnen Verbrennungsphasen im Ottomotor :

- Zündung
- Bildung des Flammenkerns, Anfangsphase der Verbrennung
- Hauptverbrennung
- Nachverbrennung

wurde beim Porsche-SKS-Motor versucht, für jede dieser Phasen optimale Voraussetzungen zu schaffen, da im herkömmlichen Ottomotor eine Trennung der einzelnen Phasen des Verbrennungsvorganges und die Bildung optimaler Bedingungen für ihren Ablauf nicht möglich ist.

2. Verbrennungsablauf im Porsche-SKS-Motor

Die Anforderungen für den optimalen Ablauf der einzelnen Verbrennungsphasen sind unterschiedlich und widersprüchlich. Für die Zündung und Entwicklung eines stabilen Flammenkernes ist es notwendig, daß die durch die chemische Reaktion freigesetzte Wärme am kleinen, vom Zündfunken erfaßten Gemischteil größer ist als die an seiner Oberfläche abgeführte Wärme. Die Strömungsgeschwindigkeiten sollen relativ niedrig sein, um nicht noch zusätzlich zu einer Verminderung der Ionisation

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und einem Anstieg der Überschlagspannung zu führen. Nach der Bildung des für die Fortführung der Verbrennungsreaktionen erforderlichen Flammenkernes ist eine hohe Turbulenz für eine rasche und vollständige Verbrennung notwendig.
Eine Optimierung für jede einzelne Verbrennungsphase wurde beim Porsche-SKS-Motor angestrebt. Der mit magerem Kraftstoff-Luft-Gemisch versorgte Hauptbrennraum befindet sich zwischen Zylinderkopf und Kolbenboden Bild 1.

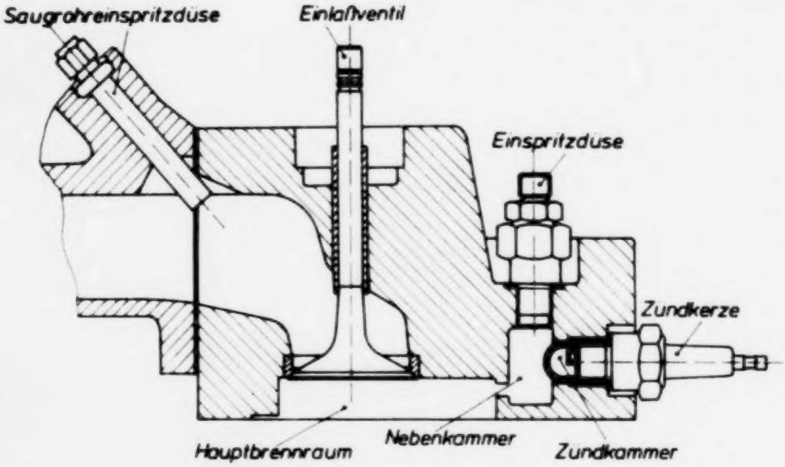


Bild 1 Porsche-SKS-Motor, Prinzipanordnung einer Brennraumform.

Er ist durch einen oder mehrere Schußkanäle mit einer kleinen Nebenkammer verbunden. Das Gemisch in der Nebenkammer wird mittels einer Einspritzdüse oder eines Zusatzventiles angefettet. An dieser Kammer ist eine weitere kleine Zündkammer angeordnet in der eine ruhigere und weniger turbulente Strömung als in der Nebenkammer herrscht. Somit werden für Zündung und Entflammungsbeginn optimale Bedingungen geschaffen. Durch die Schichtung der Ladung mit einem reichen, stets zündfähigen Gemisch in der Nebenkammer und einem sehr mageren in anderen Teilen des Brennraumes ist der Betrieb des Motors mit einer Gesamtluftzahl von $\lambda_{ges} > 1{,}0$ gewährleistet.

Wie die Versuche an Ein- und Mehrzylindermotoren zeigten, ist das SKS-Verfahren auch unter instationären Bedingungen durch eine große Stabilität des Betriebes in einem breiten Drehzahl- und Lastbereich gekennzeichnet.

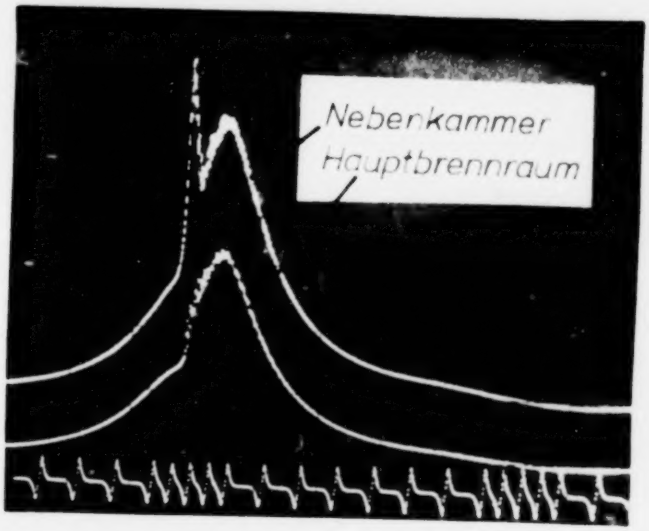


Bild 2 Indikatordiagramm des SKS-Motors.

Bild 2 zeigt ein p-α-Indikatordiagramm des SKS-Motors. Die optimalen Bedingungen in der Zünd- und Nebenkammer ergeben dort eine schnell ablaufende Verbrennung nach einem äußerst kurzen Zündverzug.

Abhängig von der Größe und der Form des Schußkanals steigt der Druck in der Nebenkammer an und die Verbrennungsprodukte der kleinen Menge des angereicherten Gemisches werden durch den Schußkanal in den Hauptbrennraum ausgestoßen. Bei einer optimierten Größe des Schußkanals sind die Ausströmgeschwindigkeiten sehr groß, was die Turbulenz der Ladung im Hauptbrennraum bedeutend intensiviert. Die in den Hauptbrennraum ausströmenden Gase können dort sehr magere Gemische entflammen. Die intensive Gasvermischung ergibt eine von mehreren Punkten weiter ablaufende Verbrennung im Hauptbrennraum, die in einer kurzen Zeit erfolgt. Der Druckanstieg im Hauptbrennraum ruft nachträglich einen Anstieg des Druckes in der Nebenkammer hervor.

Durch die rasche Entzündung des Gemisches im Hauptbrennraum und durch eine schnelle Verbrennung unter Mitwirkung einer hohen Intensität der Turbulenz, können im Brennraum mit zwei untereinander verbundenen Volumina (V_N und V_H) überlagerte Druckschwingungen entstehen. Im Unterschied zur klopfenden Verbrennung können diese aber nicht mit einer Vergrößerung der Oktanzahl des Kraftstoffes oder durch die Zurücknahme des Zündzeitpunktes beseitigt werden. Da die Amplituden dieser Druckschwingungen klein sind, stellen sie keine Gefahr für das Triebwerk des Motors dar. Ähnliche Erscheinungen in Brennkammern der Gasturbinen werden als positiv betrachtet, da sie die Vollkommenheit der Verbrennung vergrößern. Die Verbrennungs- und Druckverläufe im SKS-Motor sind im wesentlichen durch die konstruktive Gestaltung des Brennraumes vorbestimmt. Eine Änderung der physikalisch chemischen Eigenschaften des Brennstoffes hat, im Gegensatz zum Ottomotor, nur einen geringen Einfluß auf den Verbrennungsablauf.

Eine sichere Entzündung des Gemisches in der Nebenkammer des SKS-Motors ist in einem Luftzahlbereich $\lambda_N = 0,4 - 1,2$ möglich. Bei der Verwendung fetter Gemische in der Nebenkammer ($\lambda_N < 0,8$) bestehen die in den Hauptbrennraum ausgestoßenen Gase im wesentlichen aus Produkten der unvollkommenen Verbrennung. Neben CO und C_2 sind hier bedeutende Mengen an H_2, OH-Radikalen und vielen anderen Produkten der teilweisen Oxydierung vorhanden. Diese Produkte sind sehr reaktionsfreudig und dienen nach dem Eintritt in den Hauptbrennraum als Kerne der dort fortgesetzten Kettenreaktion. Mit steigender Luftzahl in der Nebenkammer nimmt die Menge an Produkten der unvollständigen Verbrennung ab, die Temperatur der ausgestoßenen Gase aber zu. Die Stabilität der Entzündung des Gemisches im Hauptbrennraum wird jedoch kleiner. Für die Entzündung des Gemisches im Hauptbrennraum ist nicht die Temperatur der ausgestoßenen Gase wesentlich, sondern viel mehr die Menge an teiloxidierten Produkten die eine schnelle Entwicklung der Kettenreaktion bewirken. Werden sehr fette Gemische angewandt, gewinnt die Wandtemperatur der Nebenkammer an Bedeutung.

Auf die große Stabilität der Entzündung und Verbrennung im SKS-Motor bei Anwendung fetter Gemische in der Nebenkammer deuten auch die geringen Schwankungen der aufeinanderfolgenden Zyklen hin. In den Bildern 3 und 4 sind die Schwankungen der Spitzendrücke für den herkömmlichen Ottomotor und der Porsche-SKS-Motor gegenübergestellt.

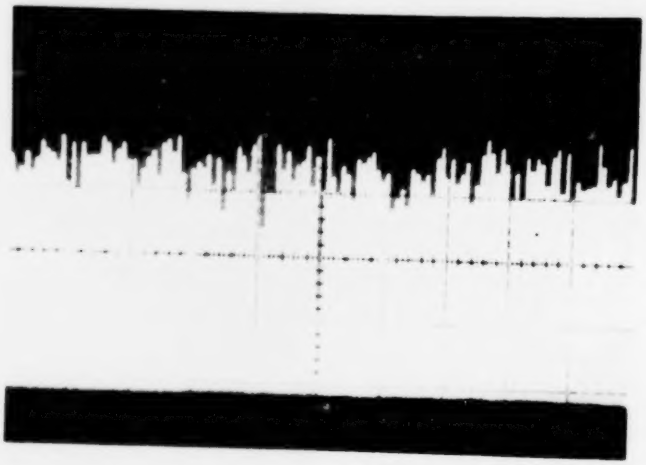


Bild 3 Schwankungen der Spitzendrücke im Ottomotor.
n = 2000U/min; w_e = 0,25 kJ/dm^3; λ = 1,10

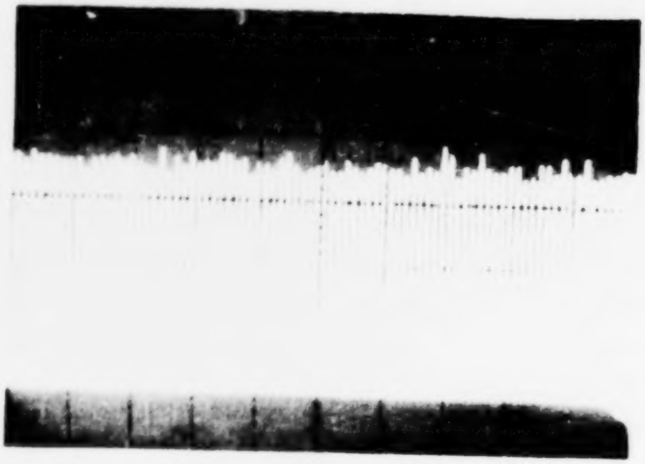


Bild 4 Schwankungen der Spitzendrücke im SKS-Motor
n = 2000 U/min; w_e = 0,25 kJ/dm^3; λ_{ges} = 1,64

3. Betriebskennwerte und Abgasemission

Bei verschiedenen Lasten und Drehzahlen wurde der Einfluß verschiedener Parameter auf die Betriebskennwerte und Abgasemission des SKS-Motors untersucht. Bild 5 zeigt die Änderung der Betriebskennwerte in einem Teillastpunkt des Einzylinder-Versuchsmotors. Bei einer nach minimalen Kraftstoffverbrauch optimierten Nebenkammereinspritzmenge könnte der Porsche-SKS-Motor bis $\lambda = 2{,}1$ abgemagert werden, wobei die Abmagerungsgrenze allein durch die maximale Luftmenge bei voll geöffneter Drosselklappe gegeben ist. Die Gesamtluftzahl des Schichtlademotors ist durch die Luftzahlen der Nebenkammer und des Hauptbrennraumes bestimmt.

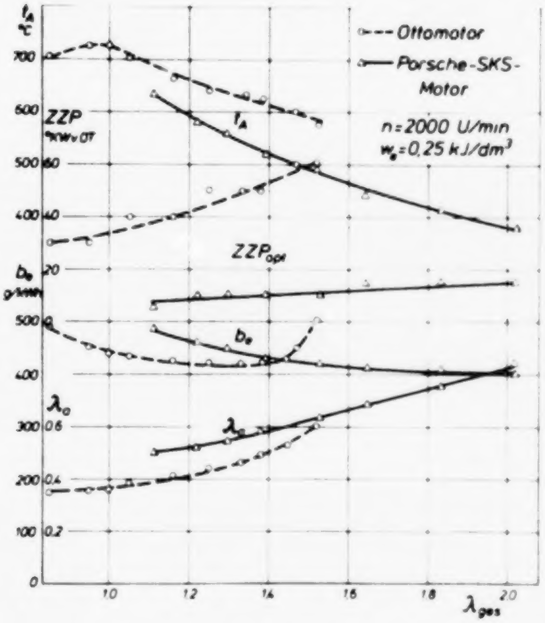


Bild 5 Vergleich der Verbrennungsverfahren.

Im unteren Lastbereich ist ein Gebiet der Gesamtluftzahl von etwa $\lambda = 0{,}8 - 2{,}2$ nutzbar. Die maximale Leistung wird wie beim Ottomotor üblich, bei etwa $\lambda = 0{,}9$ erreicht. Der Vergleich der Kennwerte des SKS-Motors mit einem Ottomotor modernster Bauweise zeigt deutlich die wesentlich größere Ausdehnung des λ-Gebietes (Bild 5). Der minimale Brennstoffverbrauch liegt bei beiden untersuchten Motoren etwa gleich. Zu beachten ist aber, daß der Ottomotor wegen der erforderlichen Abdeckung der instationären Betriebszustände üblicherweise nicht mit der verbrauchsoptimalen Luftzahl eingestellt werden kann. Die besseren Voraussetzungen für die Zündung und Verbrennung im SKS-Motor spiegeln sich in einem späteren optimalen Zündzeitpunkt wider. Bei der optimalen Größe der Nebenkammer und des Schußkanals hat eine Änderung des Zündzeitpunktes einen wesentlich geringeren Einfluß auf Betriebskenndaten und Abgasemission als beim Ottomotor.

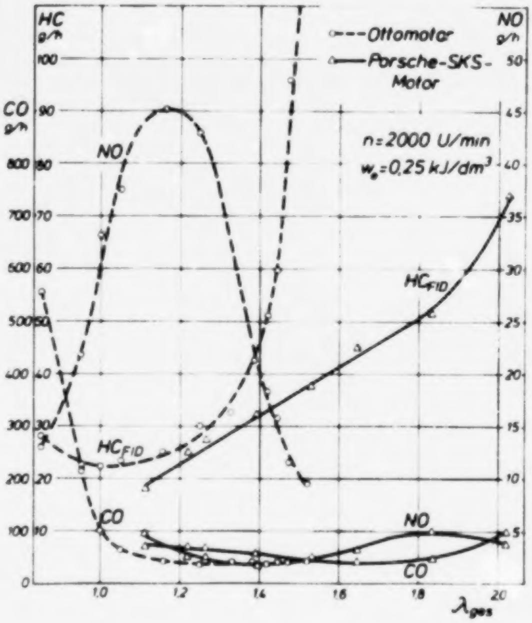


Bild 6 Vergleich der Verbrennungsverfahren.

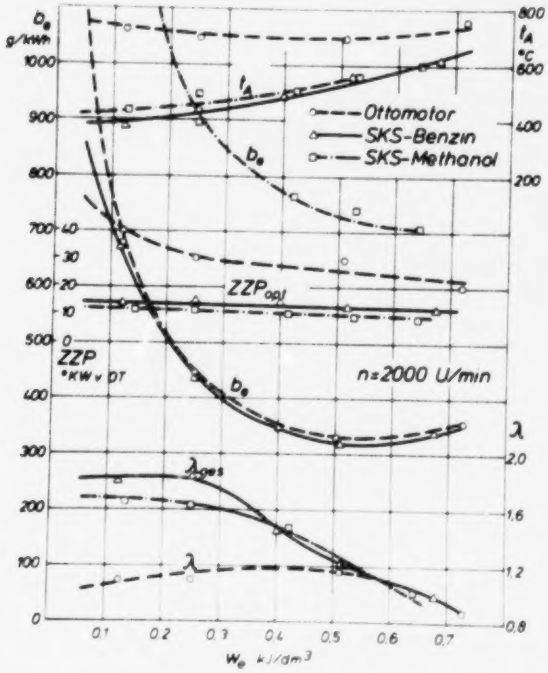
Die Messung der Konzentration der einzelnen Abgaskomponenten zeigt, daß die Verbrennungsprodukte des Schichtlademotors prinzipiell gleiche Zusammensetzung haben wie des Ottomotors.

Im Bild 6 ist die Änderung der Abgaszusammensetzung des Versuchsmotors mit einer Änderung der Gesamtluftzahl gezeigt.

In der ersten Entwicklungsphase des SKS-Motors, die im Hinblick auf geringe NO-Emission abgestimmt war, ist es gelungen, den NO-Ausstoß gegenüber dem Maximalwert des Ottomotors um 90% zu vermindern. Selbst die niedrigsten NO-Emissionen des Ottomotors bei sehr fettem bzw. sehr magerem Gemisch konnten noch um mehr als 60% unterschritten werden. Bei dieser Auslegung weist der Porsche-SKS-Motor die gleiche CO-Emission auf wie der Ottomotor im mageren Bereich, während die HC-Emission stets kleiner als beim Ottomotor ist. Unter Inkaufnahme einer Erhöhung der NO-Emission ist es möglich, durch eine andere Auslegung des SKS-Motors die HC-Emission weiter zu senken und gleichzeitig den Brennstoffverbrauch zu vermindern.

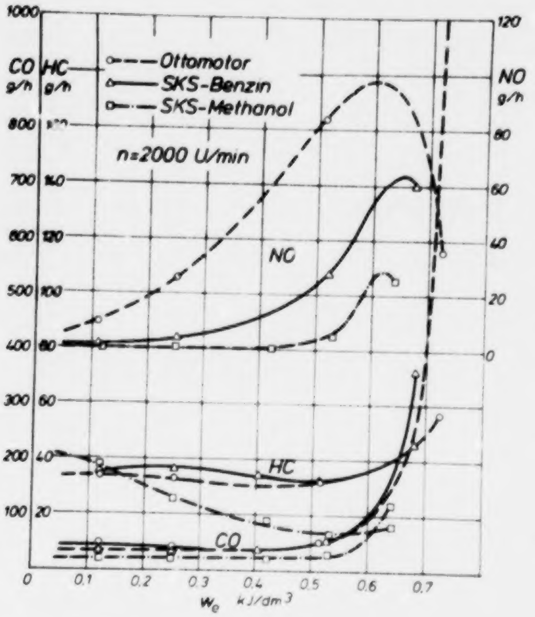
Regelcharakteristik des Schichtlademotors

Der beim Porsche-SKS-Motor wesentlich größere nutzbare Luftzahlbereich bietet die Möglichkeit, eine qualitative Regelung durch Änderung der in den Hauptbrennraum angesaugten Brennstoffmenge durchzuführen. Eine solche Regelung hat im Vergleich zur Quantitätsregelung entscheidende Vorteile, wenn stets gute Brennbedingungen gegeben sind. Bei einer zu großen Abmagerung des Gemisches besteht die Gefahr, daß die Verbrennung zu langsam abläuft. Dann bringt eine gewisse Drosselung der angesaugten Luftmenge Vorteile. Als Beispiel sind in den Bildern 7 und 8 für eine Drehzahl die optimale Einstellcharakteristik des Otto- und des SKS-Motors gegenübergestellt.



Für den Porsche-SKS-Motor erweist sich eine kombinierte Qualitäts-Quantitäts-Regelung als günstig. Im Gebiet höherer Last, wenn $P_e > 0{,}5\ P_{emax}$ ist, werden günstige Ergebnisse bei einer reinen Qualitätsregelung erzielt. Im unteren Lastbereich bringt die Quantitätsregelung Verbesserungen bezüglich des Kraftstoffverbrauches und der Abgasemission. Die Abgastemperatur als wesentlicher Faktor für die Nachverbrennung von CO und HC steigt an.

Bild 7 Abhängigkeit der Betriebskenndaten von der Motorlast.



Damit ergeben sich niedrigere Werte für die Emission dieser beiden Komponenten. Durch die Drosselung wird auch die NO-Massenemission kleiner.

Für die auf niedrige NO-Emission ausgerichtete Variante des Porsche-SKS-Motors liegt bei der Optimierung des Motorbetriebes nach dem Brennstoffverbrauch dieser sowie die CO- und HC-Emission im gesamten Lastbereich etwa gleich wie beim Ottomotor. Die NO-Emission dagegen beträgt nur 10-20% der des Ottomotors.

Bild 8 Abhängigkeit der Abgasemission von der Motorlast.

Durch die Eigenart des Verbrennungsablaufes im Porsche-SKS-Motor ist eine wesentlich geringere Empfindlichkeit auf eine Änderung der Kraftstoffeigenschaften als im Ottomotor festgestellt worden. Bei Versuchen, den SKS-Motor mit Methanol zu betreiben, wurde im ganzen Lastbereich praktisch gleiches Betriebsverhalten wie beim Benzinbetrieb beobachtet. Wesentlich größer waren die registrierten Unterschiede in der Abgasemission. In den Bildern 7 und 8 sind auch die Änderungen der Betriebskennwerte und der Abgasemission des SKS-Motors beim Betrieb mit Methanol eingetragen. Der Methanolbetrieb hat im Vergleich mit Benzinbetrieb eine Verdoppelung des Kraftstoffverbrauches verursacht, was mit seinem niederen Heizwert in Zusammenhang steht. Der effektive Wirkungsgrad η_e ist jedoch beim Betrieb mit Methanol höher als beim Benzinbetrieb. Der optimale Zündzeitpunkt ist beim Methanolbetrieb praktisch gleich wie beim Benzinbetrieb, was auf annähernd gleiche Verbrennungsgeschwindigkeiten hindeutet.

Durch den Methanolbetrieb wurde die CO-Emission des SKS-Motors um 5o-7o% reduziert. Er hat auch eine wesentliche Verringerung der gemessenen HC-Emission gebracht. Wie groß die tatsächliche Verringerung der Emission an unverbrannten Kohlenwasserstoffen beim Betrieb mit Methanol war konnte nicht ermittelt werden, da die Messung der HC-Konzentration in Abgasen von Methanol mit üblichen Meßmethoden nicht genau ist. Der Methanolbetrieb hat in einem breiten Lastbereich fast keinen NO-Ausstoß verursacht.

Zusammenfassung

Die Bestrebungen zur Verminderung der Abgasemission bei gleichzeitig niedrigem Brennstoffverbrauch führten zur Entwicklung des Porsche-Schichtlade-Kammer-Systems (SKS). Es wurde versucht, für jede einzelne Phase des Verbrennungsablaufes im Motor jeweils optimale Bedingungen zu schaffen. Daraus ergab sich ein System mit unterteiltem Brennraum und dreistufiger Verbrennung. Wie die Versuche an verschiedenen Motoren zeigten, ist das Verfahren durch eine große Stabilität des Betriebes auch unter instationären Betriebszuständen gekennzeichnet. Dabei haben viele Auslegungsparameter, wie Luftzahl, Zündzeitpunkt, Verdichtungsverhältnis, einen wesentlich geringeren Einfluß auf Betriebsverhalten, Brennstoffverbrauch und Abgasemission als beim vergleichbaren Ottomotor. Das ermöglicht eine relativ einfache Regelung des SKS-Motors.
Der Verbrennungsablauf im Porsche-SKS-Motor ist im wesentlichen durch die konstruktive Auslegung der Brennraumform vorbestimmt und eine Änderung der chemisch-physikalischen Eigenschaften des Kraftstoffes hat nur einen geringen Einfluß auf den Ablauf des Brennprozesses. Bei Versuchen mit Methanol wurde gleiches Verhalten des SKS-Motors festgestellt wie beim Benzinbetrieb. Es wurde jedoch eine weitere Reduzierung der schon kleinen Emissionen an gesetzlich limitierten Abgasbestandteilen registriert.

Development of the Perkins "Squish Lip" Combustion System.

R. Bertodo, T.W.E. Downes, I.D. Middlemiss, F. Brear.
Perkins Engines Company.
Peterborough. PE1 5NA.
England.

The Report describes the evolution of a pollution control system for small naturally aspirated direct injection "diesels". The exhaust quality of such engines was found to be largely dependant upon the air/fuel mixing rates and the spatial and temporal distribution of equivalence ratio in the combustion chamber. This realization led to the development of a new combustion system capable of meeting project future emission legislation without performance deterioration and with reduced noise levels. Typical bench and field trials data is presented. Future developments are discussed.

Le rapport de l'enquête trace l'évolution d'un système pour contrôler la pollution émise par les moteurs Diesel d'injection directe non-suralimentés. On a trouvé que la qualitée du gaz d'échappement de ces moteurs dépend, en grande partie, de la vitesse de mélange entre air et combustible de la distribution spatiale et transitoire du rapport d'équivalence dans la chambre de combustion. C'est en se rendant compte de ce fait qu'on a développe un nouveau système de combustion capable de satisfaire les législation contre l'émission gazeuse qui sont prévues, avec une reduction de bruit mais sans diminuer la Performance. Résultats typiques des épreuves sur le Banc d'Essai et à la campagne sont présentés. Les développements futures sont discutés.

Diese Abhandlung beschreibt die Entwicklung eines Verunreinigungkontrollsystems für kleine, unaufgeladene "Diesels" mit direkter Einspritzung. Die Qualität der Abgase solcher Motoren erschien grossenteils von der Luft/Brennstoffvermischung und der raumlichen und zeitlichen Verteilung des Äquivalentverhaltnisses im Verbrennungsraum abhänging. Diese Erkenntniss führte zur Etwicklung eines neuen Verbrennungsystems welches fähig ist vorauszusehende zukünftige Gesetzgebung gegen Luftverunreinigung zu treffen, bei Verringerung des Lärmniveaus, ohne Verschlechterung der Leistung. Typische Prüfstand und Feldeinsatzdaten werden gegeben. Zukünftige Entwicklungen werden erörtert.

DEVELOPMENT OF THE PERKINS "SQUISH LIP" COMBUSTION CHAMBER.

INTRODUCTION

Over the past fifty years, the "diesel" engine, through its reliability, durability and economy, has gradually established itself as the preferred prime mover for a very wide range of commercial applications. Fuel pricing and fiscal policies have often assisted this trend. Emission legislation enacted during the last decade, and current concern over the likely future availability and cost of liquid fossil fuels, has opened new opportunities for the potentially cleaner and thermodynamically more efficient compression ignition engine in market segments still dominated by the spark ignited "gasolene" engine. Major research and development programmes have been mounted by all leading manufacturers to exploit this new potential.

Published work to date suggests that, of the two main "diesel" engine variants in common use, the indirect injected type, with either vortex or swirl pre-chamber, can probably be tuned to meet the most stringent exhaust quality standards proposed by North American legislators so far for heavy duty engines. "Add-on" devices, such as exhaust gas recirculation, may be required in light duty applications. Indirect engines, however, have less favourable fuel consumption characteristics. Highly turbocharged direct injection engines have apparently also met the proposed California Air Resources Board (CARB) 1977 regulations, under development conditions at least. This approach, however, results in significant adverse cost impact when applied to engines of less than about 150 kW (200hp).

It has been generally accepted that naturally aspirated, direct injection "diesels" have unfavourable gaseous and particulate emission characteristics and that their acceptability in pollution sensitive areas would become progressively more problematic, despite their advantageous fuel economy. Such engines are currently predominant in agricultural and industrial applications World-wide, in European trucks and in class V111 vehicles ($>$15000 kg G.V.W.) in the United States. If the emissions from these engines could be controlled simply and at source, an alternative and more economic prime mover would then be available for the "gasolene" engines currently specified for most North American vehicles in the 4500-11000 kg (10000-25000lb) G.V.W. range.

The investigation described here was started to safeguard the traditional products of the Authors' Company. These are predominantly naturally aspirated direct injection "diesels" in the power bracket 30-150 kW (40-200 hp). Small high speed swirl chamber engines and turbocharged direct injection units are also produced. The main applications are agricultural, industrial and marine World-wide, with major commercial vehicle penetration in Japan and Europe.

PRELIMINARY INVESTIGATIONS

Eyzat and Guibert (1)* have demonstrated, in computer simulations of the chemical reaction

$$N_2 + O_2 \rightleftharpoons 2NO \quad . \quad . \quad . \quad . \quad (i)$$

that experimental data of NO formation at verying fractions of complete combustion can be predicted with fair accuracy. In considering the above chemical events, it is now generally accepted that in an engine cylinder the reaction $O_2 \rightleftharpoons 2O$ reaches equilibrium before nitric oxide formation becomes important. The governing reactions are, therefore, described by a Zeldovich chain (2) in which the following predominate

$$O + N_2 \rightleftharpoons NO + N \quad . \quad . \quad . \qquad (ii)$$

$$O + NO \rightleftharpoons O_2 + N \quad . \quad . \quad . \qquad (iii)$$

Temperature and temperature gradients are critical for reaction (ii) in view of the high activation energies ($k_{ii} \simeq 10^{11}$ exp (-303000/RT) l. $mol^{-1} s^{-1}$) (3) and the reaction is effectively frozen at high temperatures. Clearly, NO_x formation can be minimized either by lowering the peak temperature below the reaction value (~ 1700K) or by restricting oxygen availability. Even if turbocharging is excluded on economic grounds, there are many possible ways of attaining these objectives. The following main options were examined (4) in some detail during the present work without commercial success :

fumigation and pilot injection ;
water injection ;
exhaust gas recirculation ; and
derating, with or without injection retard.

Although these preliminary investigations were unsuccessful, it seemed clear that any practical control system would incorporate retarded injection timing as an NO_x reducing feature. Problems of light load misfire, and consequent increases in unburnt hydrocarbon emissions, would require resolution. The resultant fuel consumption penalties and high exhaust smoke levels would also have to be accommodated. In view of this, the possibility of combining a very late timed engine with catalytic converters in the exhaust manifold, for HC oxidation, and particulates filter in the silencer was considered. Although technically feasible, the proposal was not considered commercially viable and attention focussed on the in-cylinder processes.

GENERAL CONSIDERATIONS

The air motion within the cylinder of a direct injection "diesel", of the type considered here, can be broadly defined in terms of an inlet port generated tangential velocity (swirl) and a radial component (squish) largely caused by piston motion. The swirl movement is predominant. Fuel is injected, as liquid droplets, into this swirling, compressed air charge shortly before top dead centre (TDC). The core of the injected fuel stream is distorted by the air motion, as shown in fig 1, carrying away the smaller droplets to form an intermediate vapour/air region with a lean down stream leading edge. The combustion mechanism in each region varies and a delay in ignition is always evident.

Little is known about the reaction mechanisms between injection and ignition, although sampling by Garner, Morton and Saunby (5) suggests that peroxide and aldehyde intermediates are formed during the ignition delay. These reach a critical concentration and are then followed by a series of fast chain reactions leading to spontaneous ignition and combustion. If the critical intermediate compound concentrations are not reached, then partial oxidation products are formed, giving rise to odourous components in the exhaust.

In detail, ignition nucleii are formed at favourable mixture points in the heterogeneous vapour/air region (fig 1), close to the leading edge. Independent flame fronts propagate from these points giving rise to a steep fronted heat release diagram (fig 2), high local temperatures and temperature gradients. These conditions promote the formation of NO_x. The leading edge is too lean for combustion and only partial oxidation will occur with inevitable HC emissions. The width of this region, however, is temperature and pressure sensitive and hence controllable. Propagation of the flame will lead to high evaportaion rates in the spray core and consequent fast diffusion burning. Core combustion is controlled largely by the local air/fuel ratio; this in turn will establish the degree of NO_x and smoke formation. The injection tail consists mainly of coarse droplets and may be a major source of unburnt hydrocarbons and carbon particles.

The critical initial conflagration in the vapour/air region of the spray and the associated steep rise in heat release rate have been the subject of several studies. All models proposed in published work, however, are based on empirical expressions and attempts at relating pollutant formation to fundamental theory have been largely subjective. This has not prevented the development of cycle modifications aimed primarily at controlling ignition delay and burning rate so as to broaden the acceptable range of fuels and reduce noise. Such modifications could be expected to suppress NO_x formation also.

For example, it was first demonstrated in 1946 (6) that the fast rise in heat release rate could be controlled if the physical conditions within the combustion chamber were arranged to curtail the residence time of the air/fuel mixture at high temperature and pressure. This is automatically the case if the combustible mixture is formed in a limited zone adjacent to the initial ignition point. If the process is a continuing one, the flame can be made to create a travelling front sweeping across the combustion chamber. Stratification of this kind led to the Texaco Controlled Combustion System (7), well known for its quietness and tolerance of fuel quality and, more recently, for its relatively low gaseous emission levels. Unfortunately, burning continues late into the exhaust stroke giving unacceptable smoke levels when operating on diesel fuel.

Similarly, by developing a proposal of Krug(8), Meurer (9) obtained some degree of stratification, and hence heat release control (fig 2), by evaporting at a pre-determined rate, fuel injected from a single hole nozzle and deposited along the wall of a deep spherical chamber, with the aid of a fast air swirl. This system is also capable of handling a wider range of fuels generally with low radiated noise, but appears prone to odourous emissions.

In each of the above systems, an attempt is made to reduce the large local variations of air/fuel ratio found during the initial combustion in the vapour/air zone downstream of the main injection **core** (fig 1). The degree of homogeneity achieved, however, has never been quantified and the sensitivity of NO formation to the temperature levels and gradients has largely negated all rigorous theoretical treatments. In the particular case considered here, a qualitive assessment can be made by considering the main parameters affecting NO_x, smoke, and specific fuel consumption (sfc). This suggests that

$$(\text{sfc, smoke, } NO_x) \simeq f\left(Tm,\ td\ \frac{dM}{dt},\ \phi,\ \theta,\ \frac{dQ}{dt}\right) \quad . \qquad (iv)$$

where, Tm is the mean cycle temperature, td the ignition delay time, dM/dt the fuel/air mixing rate, ϕ the overall equivalence ratio (i.e. the ratio of stoichiometric to actual air/fuel ratio) θ the spacial and temporal distribution of equivalence ratio and $dQ/_{dt}$ the diffusion burning rate. The ignition delay time is due partially to chemical factors, essentially functions of temperature and fuel quality, and partly to physical conditions primarily determined by $dM/_{dt}$. Further, if fuel is assumed to burn only from the vapour state,

$$dQ/_{dt} \simeq f\ (dM/_{dt}) \quad . \quad . \quad . \qquad (v)$$

Consequently, for a given fuel, fuelling rate and injection timing

$$(\text{sfc, smoke, } NO_x) \simeq f\ (dM/_{dt},\ \theta\ ) \quad . \quad . \qquad (vi)$$

It follows that a more evenly distributed equivalent ratio in both time and space would assist NO_x suppression. High mixing rates would benefit predominantly smoke control and sfc.

IN-CYLINDER AIR FLOW MODIFICATIONS

In an attempt to increase the mixing rate, and possibly at the same time even out the air/fuel ratio in the chamber, thereby allowing a greater degree of injection retard at acceptable sfc and smoke levels, List (10) devised an inlet port capable of generating both forward and reverse swirl simultaneously. This created a high degree of turbulence within the combustion chamber and, when used with high fuel injection rates, rendered the smoke-limited power less sensitive to injection timing. The application of an inlet port of this kind to a V8 naturally aspirated engine of about 8.85 l (540 in^3) capacity confirmed that the engine could be retarded sufficiently to meet the California Air Resources Board (CARB) projected 1977 levels with a 5% derate and at a marginally acceptable smoke level. A fuel consumption penalty of 8% was noted (11).

It appeared conceivable that, with development, the general performance of the engine could be improved to allow some margin for production scatter and service deterioration, but the scope for long term improvement seemed limited. A number of inlet port experiments were embarked upon in an attempt to clarify the significant features of the List port without major achievement : almost any increase in combustion chamber turbulence appeared beneficial. Some success was obtained by combining a conventional directional inlet port with a masked valve arrangement to split the air flow and generate interactions within the cylinder. In most cases volumetric efficiency problems were encountered.

It was at this juncture that consideration was first given to increased piston induced air motion. Claims of reduced smoke emissions are to be found in the literature for combustion systems incorporating squish air motion alone. Tests on standard engines did not confirm such claims (12). Modifications aimed at maximizing squish flow velocity did not improve smoke control sufficiently (4)(13), but reduced sfc degradation at retarded timing.

It seemed feasible to suppose that a strengthened squish flow component could be made to interact with conventional swirl motion so as to create a significant degree of turbulence within the chamber. This turbulence would lead to high fuel/air mixing rates in a manner similar to those induced by the interaction between the forward and reverse swirls of the List port.

THE "SQUISH LIP" COMBUSTION SYSTEM **

Initial engine tests (14) were mounted on a small 3-cylinder agricultural and industrial engine 2.5 l (152 in^3) capacity rated at 31.6 kW (42½ hp) and 37.5 r/s (2250 rpm).

Steady state flow visualization tests were carried out to define the characteristics of the inlet port and optimize the swirl component. This was followed by hot-wire anemometer measurements from a motorized engine to verify assumptions regarding the influence of piston motion. These tests confirmed that a high squish component could be generated in a running engine and that this gave rise to vigorous motion within the combustion chamber. This data was judged to be sufficiently encouraging to warrant full scale engine testing. To satisfy the squish velocity requirements, a flat bottomed combustion bowl having a 30% smaller diameter and 43% greater depth than the standard engine was used. The piston/cylinder head clearance was also reduced.

These initial tests revealed that smoke and thermal control had not been established. Opacity levels in the range 15-20% were recorded on the USPHS meter (5-6 Bosch units). These remained essentially constant as the engine was retarded to 8° BTDC, the fuelling rate being increased to maintain the original power. At this late injection timing, combined (NO_x + HC) levels of 7.6 - 8.7 g/bhp.h were recorded on the 13-mode CARB cycle. An 8% sfc degradation was noted.

It appeared likely that at retarded injection, the reduced time available led to considerable spill of the burning mixture. Iron pentacarbonyl tracer tests showed clear indication of fuel deposition high on the bowl periphery. A revision to the bowl geometry to delay spillage appeared justified; this could be done by narrowing the combustion chamber throat and restoring the volume by either deepening the bowl or increasing its maximum diameter. Practical considerations of gudgeon pin location, piston dynamics and piston head depth favoured a shallow bowl profile. Experimentation was, therefore, directed towards a wide shallow bowl with re-entrant lip (fig 3).

A series of tests were conducted with various throat openings and flank angles using injection patterns with various holes and cone and spray angles. A conventional rotary fuel injection pump was used, timing being varied manually to suit the engine characteristics. Smoke control improvements were almost immediately apparent and by progressive optimization the NO_x levels were reduced below 4g/bhp.h on the CARB 13-mode cycle at smoke levels in the neighbourhood of 7½% (2½ Bosch). Unburnt HC levels exceeded 1g/bhp.h and work now centred on its improvement and in obtaining a better understanding of the combustion mechanism.

SQUISH-LIP COMBUSTION

Activities aimed at clarifying the combustion mechanism have been severely curtailed by the foreseen timing of legislation. This has effectively denied the opportunity for a rational and systematic development programme. As a result, the work has progressed largely as a series of "cut and try" experiments. Some tentative conclusions have been reached and this, so far, has been adequate to allow exploitation on other engines.

Greased surface tests on motorized engines coupled with iron pentacarbonyl streaking and examinations of carbon deposits on combustion chamber walls have consistently confirmed that the calculated high squish velocities are probably achieved in practice and that these yield high in-bowl air movements. It is assumed that high mixing rates are generated in the restricted throat and relatively shallow bowl. High compression ratios (typically 21:1) and smooth cylinder head and piston surfaces free from recesses or valve cut outs are required and some restriction on valve overlap has to be accommodated.

Available evidence suggests that the air/fuel charge travels rapidly along the underlip and down towards the bowl floor forming a primary toroidal flow with a secondary swirling motion. The reverse flow, caused by the piston as it withdraws from TDC, is highly disruptive and the gases exhaust through the combustion chamber throat in a vigorous vortex. The initial swirl/squish velocity ratio is critical and on at least one engine major inlet port modifications are contemplated.

Conventional multi-hole fuel injection equipment of typical hydraulic performance is used, as discussed later, but the rate of pressure rise is largely independant of ignition delay (4). This, and the absence of a high initial heat release stage (fig 2), lead to the conjecture that the primary toroidal flow causes intensive evaporation of the charge. Fuel "patches" are known to form along the under lip : this is presumably promoted by the chamber geometry and injection pattern. Continuous wall evaporation of the kind described by Meurer (9) does not occur. Recycling of the partially oxidized mixture through the burning zone, located below the lip, probably occurs lowering oxygen availability and hampering NO_x formation. The combustion system has a late optimum injection timing and this leads to lower diffusion flame temperatures.

Soot formation and burn-up, and hence smoke control, are governed by extremely complex reactions and the control mechanism in the system considered here has not been finally established. However, soot formation is inversely proportional to some function of the diffusion burning rate and directly related to the diffusion flame temperature. Similarly, soot burn-up increases with higher diffusion flame temperatures and residence time, particularly if accompanied by recirculation of carbon particles through the combustion zone.

The predominant factors, in the present case, are probably the high values of $\frac{dQ}{dt}$ and residence time tr, i.e.

$$\text{(smoke)} \simeq f\left(\frac{dQ}{dt}, tr, \;\right) . \qquad . \qquad . \quad \text{(vii)}$$

Some eleven engine designs have from time to time incorporated pistons with re-entrant combustion chamber profiles. Indeed, such chambers were tested by some of the Authors' colleagues as long ago as 1958 in an endeavour to obtain higher specific powers and thermal efficiencies, but finally rejected because of poor smoke control and suspected piston vulnerability at optimum timing. The geometric shape of the chamber should be recognized as being secondary to the creation of faster air/fuel mixing rates, rapid diffusion burning and equalized air/fuel ratio across the chamber in line with eq. (v) and (vi), by what ever means this might be achieved. The geometric bowl feature, although a central and essential part of the Perkins "Squish Lip" combustion system is not a unique way of attaining such conditions in a "diesel" engine cylinder.

HC CONTROL

High fuel injection pressures are an alternative way of approaching the high mixing rates required for pollutant control at retarded timing. This option has not been pursued for economic reasons. Further, engines manufactured by the Authors' Company are equipped, almost exclusively, with a constant end of injection (CEI) rotary fuel pump restricted to delivery pressures not exceeding about 42-43 MN/m^2 ($\sim$ 6000lb/in^2), equivalent to a nozzle breaking pressure of the order of 200 atms. There are a number of significant implications associated with the fuel injection equipment requirements.

Since the high mixing rates are attained almost entirely by in-cylinder modifications, the fuel delivery characteristics must be closely tailored to the engine behaviour. This implies the need for a capability to automatically alter the injection timing with both load and speed simultaneous in accordance with a pre-determined plan. Such variations are more readily and reliably obtained by hydraulic manipulation on a rotary pump, than by the complex mechanical links required on an inline pump. Fig. 4 illustrates a typical timing plan. These variations cannot be obtained with current production pumps and special modifications are being developed by fuel injection equipment manufacturers in support of the "Squish Lip" combustion system programme.

Initial tests using semi-manual prototype pumps indicated excessive HC levels. These were identified as due to excessive inertia in the injector moving parts and too large injector sac volumes. By reducing the injector inertia by 40% and the sac volume from 0.6 to 0.3 mm^3, HC values below 1g/bhp.h on the CARB 13-mode cycle were obtained. Some production problems are foreseen in combining a small sac volume with the wide spray angle required by the system.

DETAILED CHARACTERISTICS

The new combustion system has an optimum dynamic injection timing of 8° BTDC. At this timing, the system is up to 7% more efficient than the standard direct injection engines, the combined (NO_x + HC) levels on the CARB 13-mode cycle are in the neighbourhood of 7½ - 8g/bhp.h and the lugging smoke level does not exceed 7½% on the USPHS meter. Retarding the timing to 3° BTDC degrades the thermal efficiency to a level comparable with that of a conventional high swirl direct injection engine, but reduces the emission level on the 13-mode cycle below 5g/bhp.h at opacity levels of the order of 5% (~ 2 Bosch) at peak torque (4). Typical emission levels are shown in fig.5.

Heat balance data have indicated a full load thermal efficiency of 31.5 ± 3%, when timed for low emissions, rising to 33.4% at a timing coincidental with maximum fuel economy. This compares with 32.5% for the standard direct injection engine. Fuel economy is significantly better than for the standard engine at low speeds and progressively degrades as rated speed is approached (fig.6). This is due predominantly to the longer heat release time and losses through the chamber throat. The degradation occurs at sufficiently high rotational speed to give better calculated efficiencies on representation operating cycles, and significantly better than for indirect engines (fig.7). More detailed analysis of the heat balance data showed a general redistribution of heat rejection to the cooling system, due to the lower cycle temperatures, with higher heat to exhaust and lubricating oil, as a result of the late timing. There are potential mechanical problems associated with this, as discussed later.

The late injection timing, coupled with the smoother heat release rates, give major reductions in peak firing pressures and their related rates of pressure rise. Typically (fig.8), peak pressures are reduced from 9.65 MN/m^2 (1400lb/in^2) to 6.55 MN/m^2 (950lb/in^2) and rates of pressure rise from 0.83 MN/m^2/deg.crank (120lb/in^2/deg.crank) to 0.28 MN/m^2/deg.crank (40lb/in^2/deg.crank). This implies that combustion takes place at more nearly constant pressure helping to reduce sensitivity to fuel quality. This has been confirmed by extended running with selected fuels in the Cetane Rating range 38-62 without difficulties. Since combustion generated noise is extremely sensitive to rates of pressure rise, reductions of about 3dB(A) at 1m have been recorded from bare engines in anechoic chambers. The reductions are particularly significant since the rate of pressure rise is only marginally affected by the ignition delay and hence by fuel quality and cycle to cycle variations.

MECHANICAL RELIABILITY AND DURABILITY

Twelve of the 2.5 l (152in^3) capacity engines described earlier have been assembled to assess the likely manufacturing vulnerabilities and establish reliability and durability data. Six of the engines were allocated to bench testing : three of the remainder are currently with outside operators in agricultural tractors and three in tracked front loaders on construction sites. Their cumulative running time is 837 h, with the longest machine on 316 h. The only defect recorded to-date has been a main bearing failure due to in-built dirt. The six bench test engines have accumulated about 3000 h, partly on full load full speed operation and partly under cyclic load conditions. The longest running engine has accumulated over 1800 h.

In addition, two 6 cylinder engines of about 5.8 l (354in^3)

capacity currently rated at 89.2 kW (120 hp) and 46.4 r/s (2800 rpm) and a batch of 8.85 l (540 in^3) capcity V8 engines rated at 134 kW (180 hp) and 42.7 r/s (2600 rpm) are being endurance tested with a second generation "Squish Lip" combustion system giving improved fuel economy over the wider speed range required for automotive applications. These latter engines have accumulated 4446 h, the longest running engine has successfully completed 1000 h under full load full speed conditions, followed by a further 1000 h on a 4 minute full load, 2 minute no load cycle. The condition of the relevant components from these engines were found satisfactory as discussed elsewhere (4).

The general experience with the above engines so far has highlighted the new combustion system's sensitivity to injector location, injection timing and piston to cylinder head clearance. With the engine dynamically timed, the injector located within 0.12 mm (0.005") of the desired position in any direction and the piston/cylinder head clearance at TDC held within 0.06 mm (0.003") of nominal, a combined (NO_x + HC) range of 4.0 - 6.2 g/bhp.h, on the CARB 13-mode cycle, was obtained from the twelve 2.5 l (152 in^3) engine sample (fig. 8). About half of the variation was due to the timing sensitivity, characteristic of all low emission engines. Work is currently in hand to establish with greater certainty the causes of emission scatter. Greater reductions in emission levels are also being sought to provide a wider tolerance margin.

THERMAL LOADING

Although the combustion chamber surface area/volume ratio is high, less heat is apparently transferred to the piston. This is probably due to the lower mean gas temperatures and to combustion being centred below the lip where the metal cross sectional area is relatively small, thus offering resistance to heat flow into the piston. The nett effect is a concentration of the high temperature around the bowl throat with greater top land expansion and lower top ring groove temperature. The piston lip is obviously vulnerable. Only two failures have been recorded so far : one after 500 h at 35% overload and a second following a nozzle tip failure. Nevertheless, an elaborate development programme aimed at evolving a suitable lip armouring has been mounted.

There is ample evidence to show that more heat is transferred to the cylinder head than in a conventional direct injection engine. During the expansion stroke, the gas stream emerging from the bowl throat is highly turbulent and heat transfer rates are consequently high. This leads to greater cylinder head distortion with consequent valve sinkage and, in particularly severe cases, cylinder head cracking between valve ports. On early endurance engines up to 1 mm (0.040") valve sinkage was recorded in 500 h running. This led to the adoption of heat resisting seat inserts and higher grade exhaust valve materials. Cooling passages between valve ports are being introduced on engine running at automotive ratings.

LUBRICATION

All engines have been tested using MIL-L-46152 lubricating oils. Provided the piston profile was adjusted to accommodate the new hot shape, no difficulties of lub. oil control were met.

It appears likely that, in view of the lower firing pressures and reduced ring groove temperatures, a revised piston ring pack will be incorporated in future engine builds. The use of temperature controlled skirt pistons is being considered, as a means of capitalizing further on the lower gas pressures to reduced part load noise levels.

The combustion system generates a higher level of benzene insolubles : this was typically of the order of 1½ - 3% after 200 h. This is about midway between levels recorded for conventional direct injection and prechamber engines of similar capacities.

FUTURE PROSPECTS

The new combustion system evolved during the investigation described here, has demonstrated a practical method of exhaust quality control from small heavy-duty naturally-aspirated direct injection "diesels", simply and at source, without significantly affecting their performance. In achieving, in development at least, the projected CARB 1977 levels, only marginally lower smoke levels have been recorded. Current legislation trends suggest that such low emission levels may never have to be met outside N. America, and possibly Japan and Scandinavia. In Europe, where the EEC72/80 regulation currently calls for CO and HC levels of about twice the CARB 1973 requirements but on a different cycle, NO_x concentrations are not limited at all. Tighter smoke and odour legislation would appear more likely.

Although later builds of the "Squish Lip" system has consistently returned HC levels of around 1g/bhp.h on the 13-mode cycle and subjectively been agreeably free from odour, no practical way of achieving the higher $\frac{dM}{dt}$ values needed to reduce opacity levels below about 5% on the USPHS meter, have been uncovered so far, other than by increasing injection pressures. This is outside the capacity of the equipment available. Some improvements could conceivably result from advancing the injection timing towards optimum and taking advantage of the higher thermal efficiency to de-fuel to the original rating. This would however, yield higher NO_x values and increase mechanical vulnerabilities, due to the higher gas pressures and cycle temperatures. Clearly, much further work is required if divergent N. American and European legislation is to be met with a single engine specification. In the meantime, a second generation "Squish Lip" system having lower losses, thus allowing operation up to vehicle engine speeds without consumption penalties, has been evolved and is currently being tested under field conditions.

The energy crisis has coincided with a fuller realization that liquid fossil fuels are unlikely to be able to support planned consumption growth rates much beyond the next decade or two. Attention is already turning to shale and coal derivatives. By the end of the decade synthetic methanol, ethanol and coal derived liquid fuels could be supplementing the transportation fuel inventory. In view of this, the ability of the new system to handle a somewhat broader range of fuel specifications is considered relevant and is being pursued further.

The application of emission control features of the kind described should allow the development of "diesels" having firing pressures and rates of pressure rise, and hence structural weights, more nearly comparable with those of "gasolene" engines and generating lower noise levels. Some scope for improving mechanical efficiencies has also been noted.

CONCLUSIONS

The exhaust quality of naturally-aspirated direct-injection "diesels" can be improved by reducing the mean cycle temperature or controlling the characteristically high initial rate of heat release. An examination of recognised methods of achieving these effects showed that they were not commercially viable for engines in the approximate power range 30 - 150 kW (40 - 200 hp).

A qualitative assessment of the problem led to the development of a new combustion system having high air/fuel mixing rates and fast diffusion burning. This allowed combined (NO_x + HC) levels of the order of 5g/bhp.h to be attained over the CARB 13-mode test without significant performance penalties.

Bench and field testing has so far proved encouraging and a second generation system is being evaluated for truck applications.

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* Numbers in parenthesis designate References at end of Paper.

** This is a registered trade name.

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A.V.L. Report No. 436, Jan 1974.

12. SCOTT, W.M.,
A study of the effects of exhaust emissions on engine and fuel injection equipment variables carried out on a single cylinder direct injection engine.
RICARDO External Report No. 600, Feb. 1973.

13. BERCHTOLD, M., BLOCHLE, K.F.
Evaluation of a quiescent diesel combustion chamber.
ZURICH FEDERAL POLYTECHNIC Report No. 309, March 1974.

14. BERTODO, R.
Pollutants from automotive sized engines, with special reference to "diesels".
JOINT IRCCOPR and NERC SEMINAR, London, May 20th, 1974.

Fig 1 - Injection and ignition characteristics.

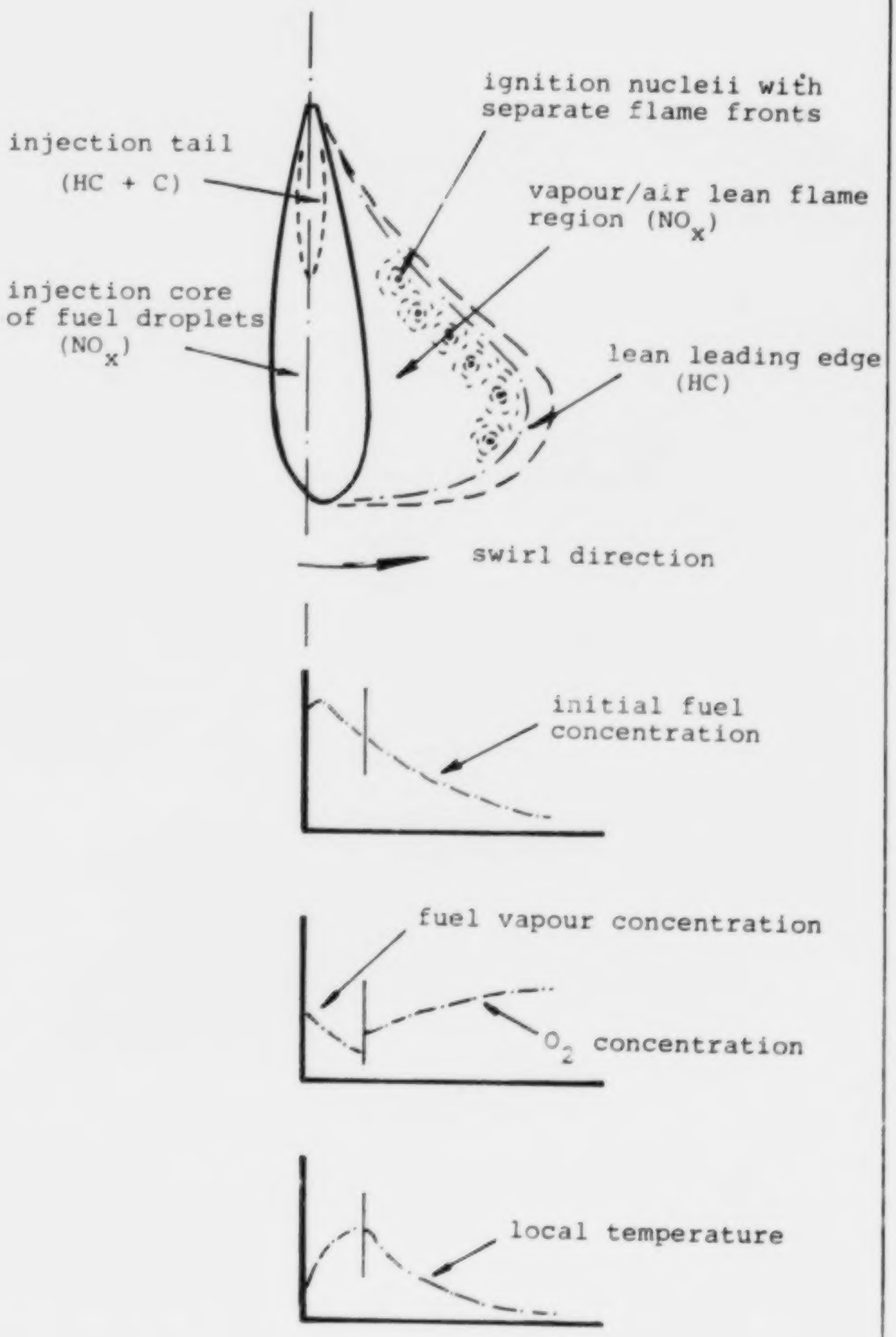

ignition nucleii with separate flame fronts
injection tail
(HC + C)
vapour/air lean flame region (NO_x)
injection core of fuel droplets
(NO_x)
lean leading edge
(HC)
swirl direction
initial fuel concentration
fuel vapour concentration
O_2 concentration
local temperature

Fig 2 - Heat release rate various "diesel" combustion systems. (1 KJ ≃ 0.95 Btu)

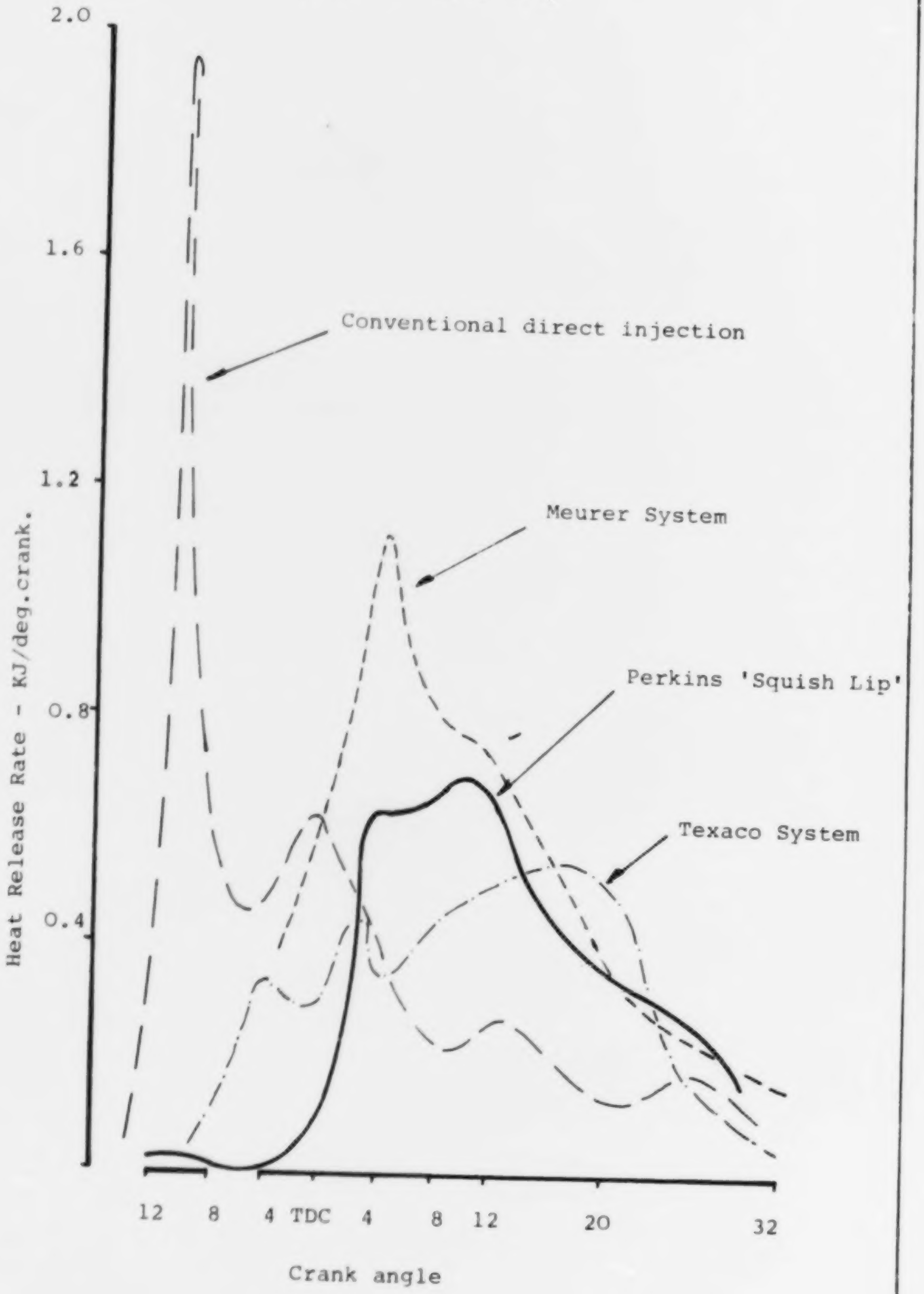
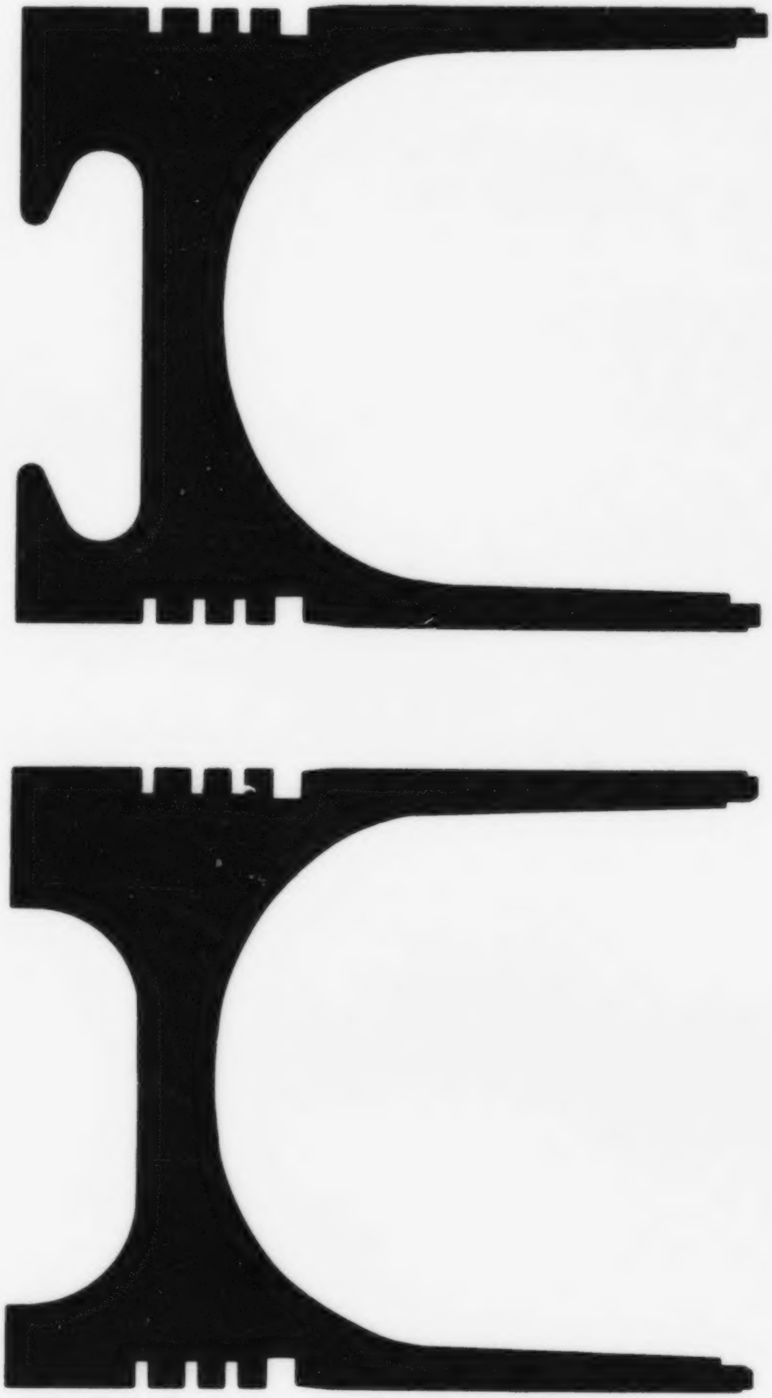


Fig. 3.



The new Perkins Squish Lip Combustion Chamber

Standard Combustion Chamber

Fig 4 - Typical fuel injection pump timing for 'Squish Lip' combustion system.

Engine Perkins D3.152
Rating 42½ bhp @ 2250 rpm
Timing 3° BTDC at full load and speed
Emissions 4.8g/bhp.h (NO_x + HC) 13-mode cycle

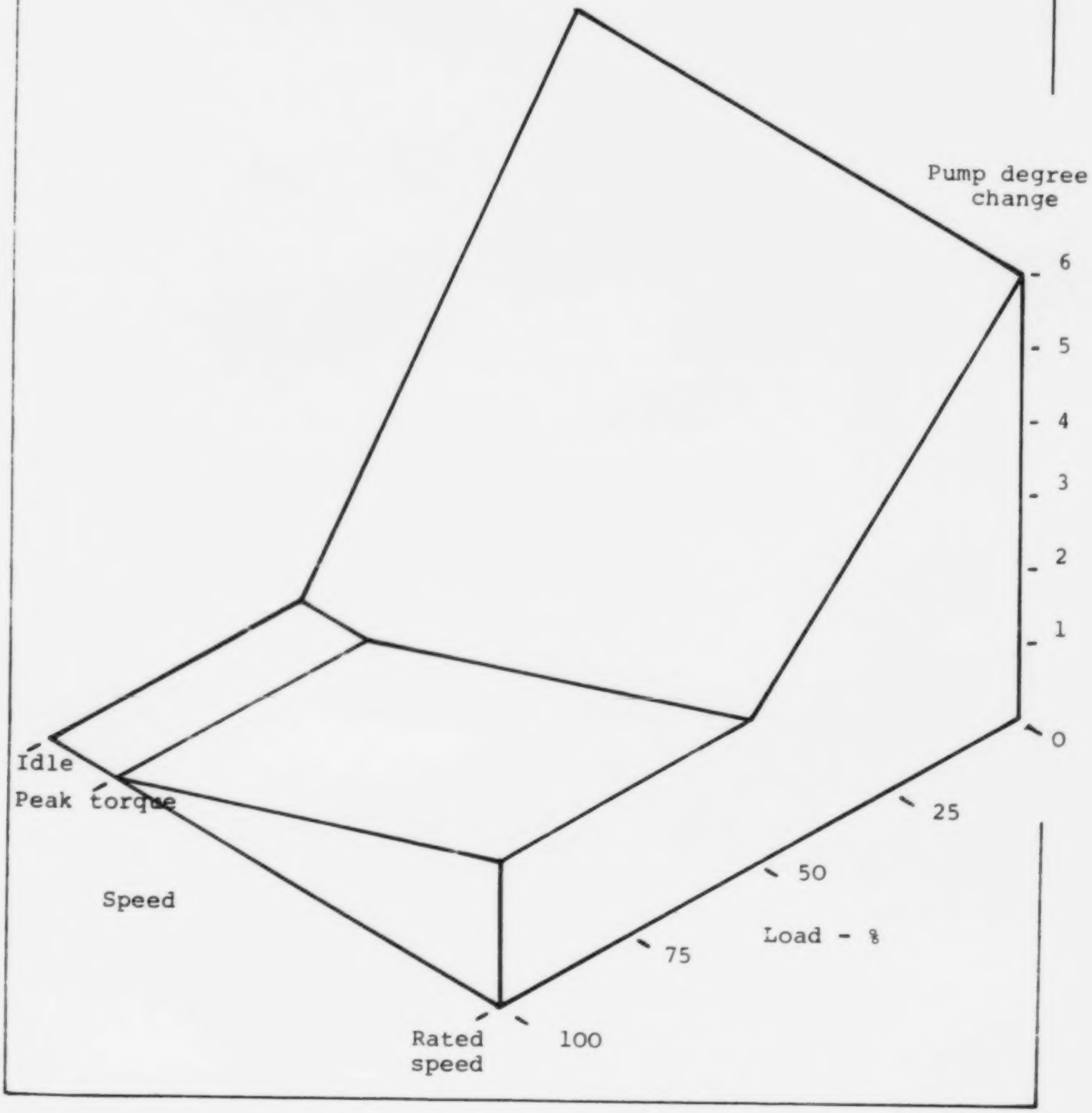
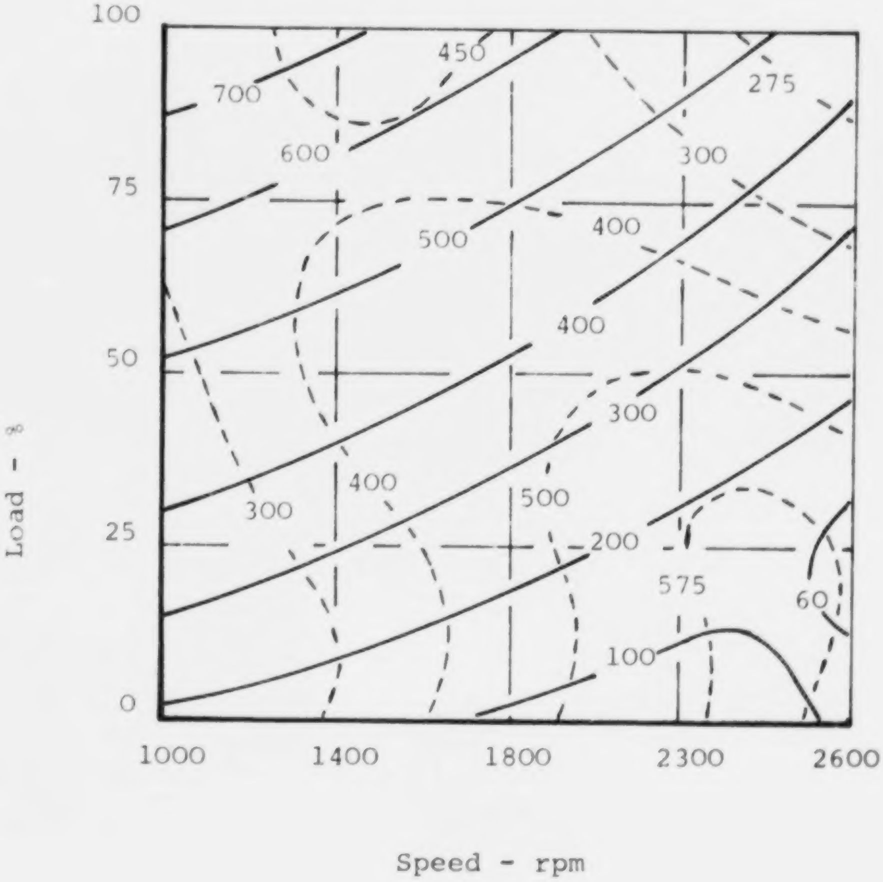


Fig 5 - Typical emission characteristics of 1st generation 'Squish Lip' combustion system

- - - HC ppmc

—— NO_x ppm



compression ratio 21:1

full load timing 3^{o} BTDC

CARB 13-mode level 4.8g/bhp.h(NO_x + HC)

Fig 6 - Comparison of standard and "Squish Lip" Perkins D3.152 engine characteristics (mean of six engines)

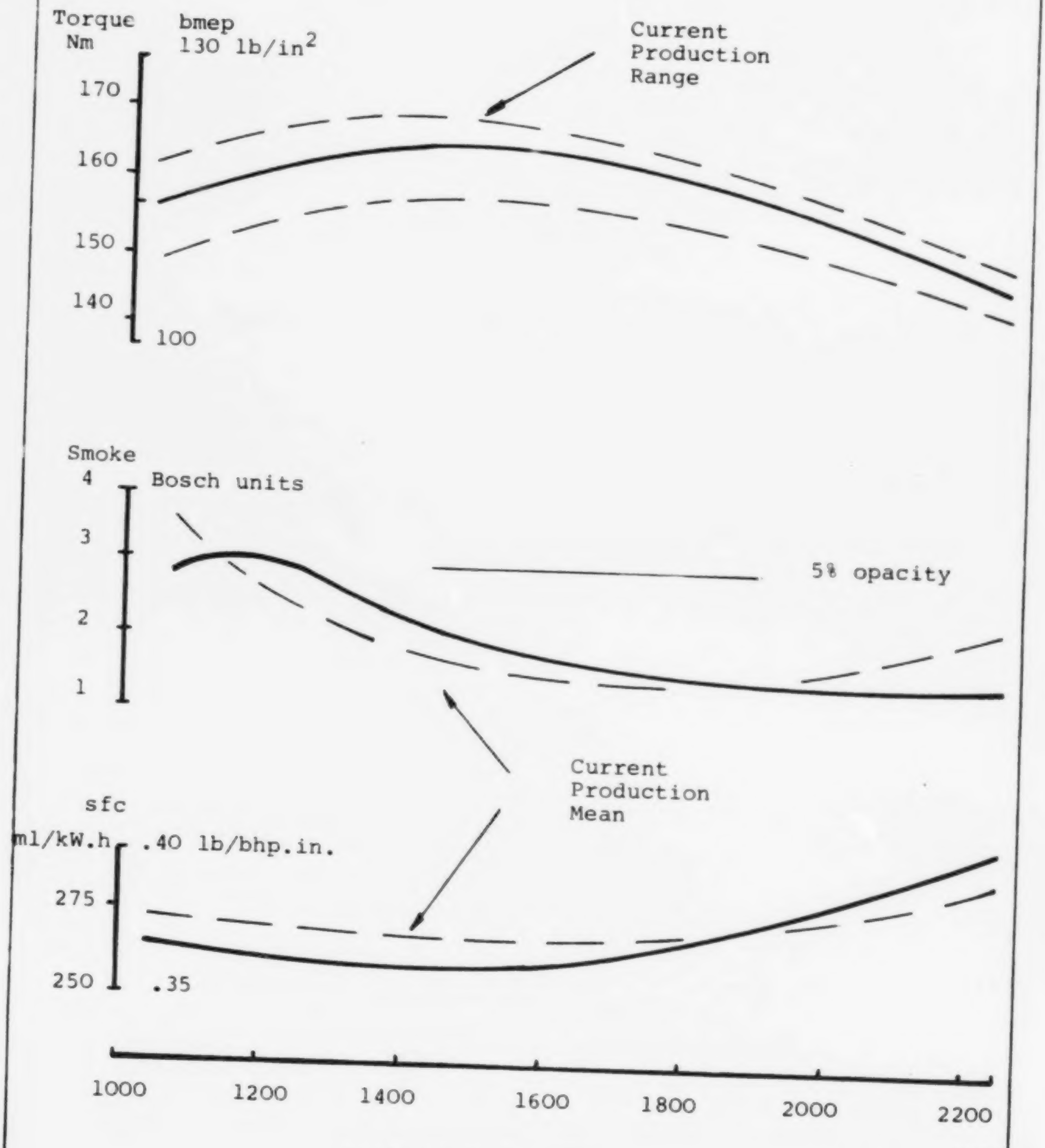


Fig 7 - Relative Fuel Consumption of various combustion systems

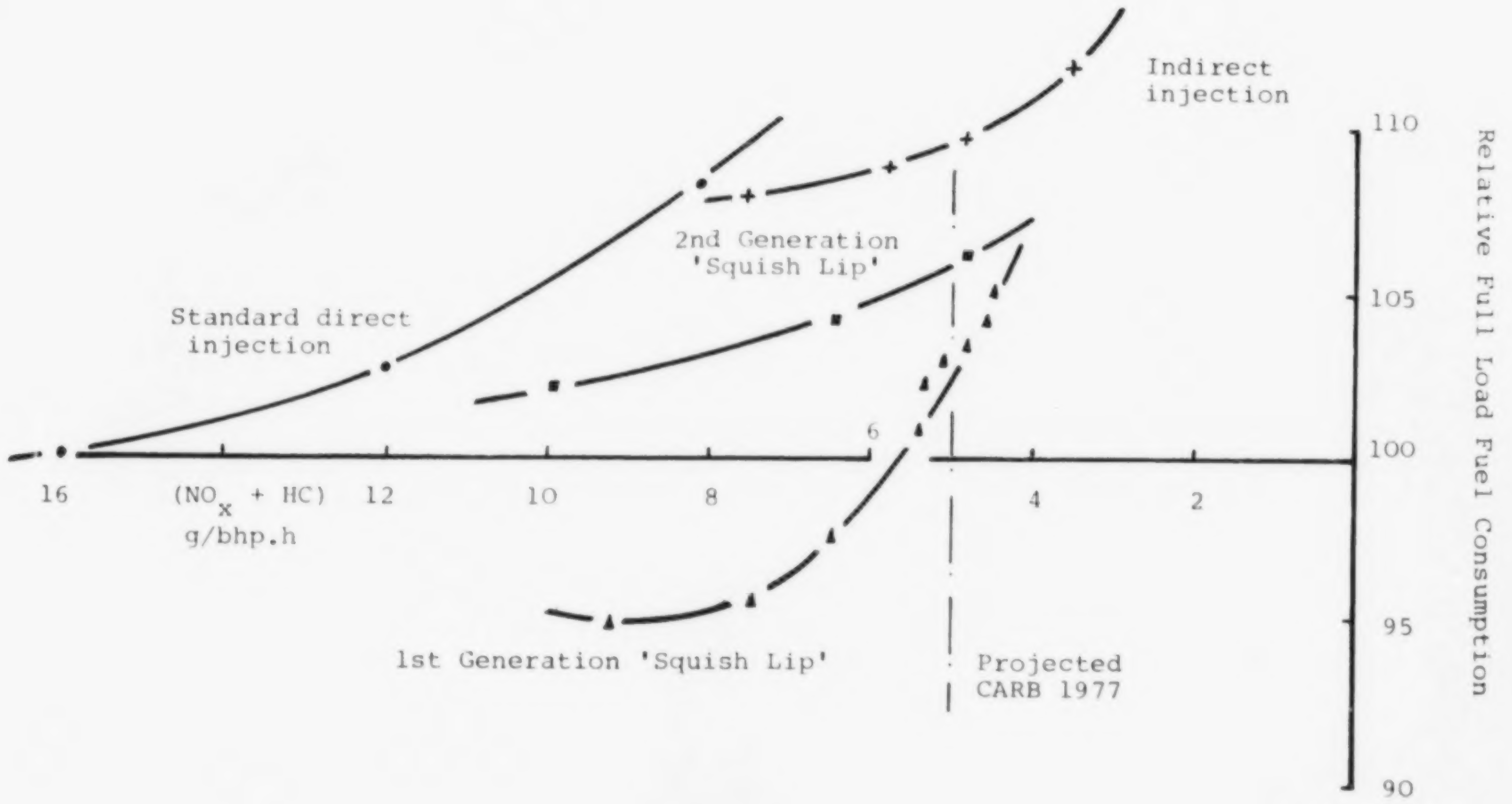
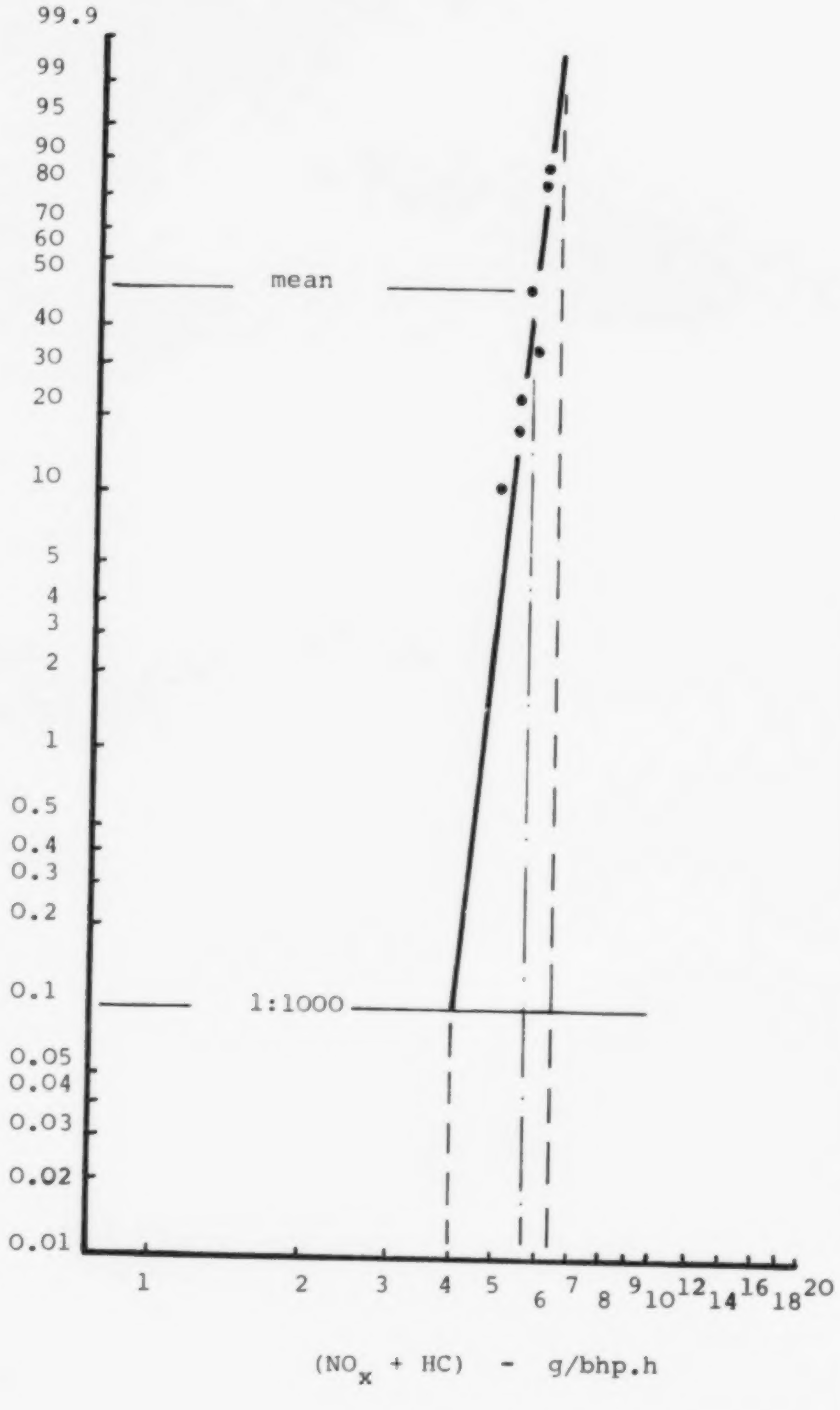


Fig 8- Exhaust mass emission scatter of twelve 3-cylinder 'Squish Lip' combustion engines (CARB 13-mode cycle)



THE MERCEDES-BENZ LDV DIESEL ENGINE

K.OBLÄNDER and H.G. SCHMIDT
Daimler-Benz Aktiengesellschaft
D7 Stuttgart 60
Postfach 202

Aside from its application as power plant for HD vehicles the diesel engine becomes increasingly important also for passenger cars and small utility vehicles. Reasons are high economy, low emissions, excellent driveability and smoothness. It is explained why Daimler-Benz uses a different combustion process for passenger cars than for trucks. Features of the prechamber-diesel are explained in detail.

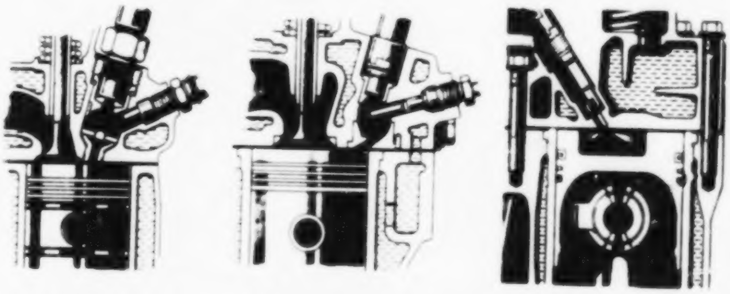
Outre son utilisation sur véhicules utilitaires, le moteur diesel prend également une importance croissante dans la propulsion de voitures particulières et de camionnettes. Une économie élevée, de faibles émissions toxiques et une grande souplesse de fonctionnement en sont à l'origine. Il sera expliqué pour quelle raison Daimler-Benz adopte sur les voitures particulières un autre procédé de combustion que sur les véhicules utilitaires. On montera, à l'aide de diagrammes, les propriétés du moteur diesel à chambre de précombustion.

Neben dem Dieselmotor als Antriebsmaschine für Nutzfahrzeuge gewinnt auch der Dieselmotor als Antriebsart für den Personenwagen und für kleine LKW zunehmend an Bedeutung. Die Gründe dafür sind hohe Wirtschaftlichkeit, geringe Schadstoffemission und gute Laufruhe. Es wird erläutert, warum Daimler-Benz für den Personenwagen ein anderes Brennverfahren verwendet als für Nutzfahrzeuge. Die Eigenschaften des Vorkammer-Dieselmotors werden anhand von Diagrammen erklärt.

Introduction

The customer used to gasoline engines will expect better economy as well as similar smoothness from a passenger car with diesel engine. Superior economy of the diesel engine becomes particularly apparent with low emission standards. A light duty vehicle (LDV) with diesel engine will meet the U.S. Emission Standards of 1975 without any special modifications, whereas a comparable gasoline engine requires a catalytic converter or a thermal reactor, EGR and air injection. It is well known that the Diesel exhibits lower specific output per unit engine weight due to its different combustion process, and, therefore, production cost per horsepower is inherently higher as in the case of a gasoline engine.

Selection of Combustion System for LDV Diesel



PRE-CHAMBER SWIRL-CHAMBER DIRECT-INJECTION

FIG. 1 - COMBUSTION SYSTEMS FOR LDV-DIESEL-ENGINES

Choice of the optimal combustion process for LDV diesels has to be a compromise between good economy, low emissions and a low noise level, Fig. 1. Daimler-Benz, therefore, employs the pre-chamber (PC) combustion process. Other manufacturers have decided on the swirl-chamber (SC) system which is fairly similar. The direct injection (DI) system is an alternative to these two systems. This alternative is frequently applied for trucks and buses. On an experimental basis Daimler-Benz has developed and tested prototype LDV engines both with direct injection and with swirl chambers. In the case of utility vehicles economy is most important. However, for LDV's further criterions have to be considered in the choice of the optimal combustion system.

The small displacement per cylinder, as well as the wide speed range of LDV diesels result in the following drawbacks of the direct injection system as compared to the prechamber system selected by Daimler-Benz.

1. Unfavorable Ignition (longer ignition delay)
   As Fig. 2 shows, the rate of pressure rise is about three to four times higher, and peak pressures are increased by 30 bar. In both respects the swirl chamber shows intermediate values between the DI and the PC system.

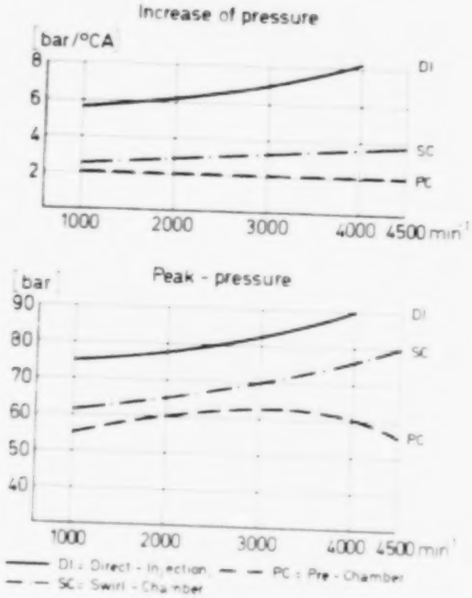


FIG. 2 - INCREASE OF PRESSURE AND PEAK-PRESSURE (LDV-DIESEL-ENGINES)

2. Loss in Volumetric Efficiency
   The air swirl required in the combustion chamber of DI engines results in about 5 % loss of maximum power.

3. Cold Start
   DI engines with small displacement have their cold start limit at about -5 °C (23 °F), whereas in a truck engine this will be in the order of -18 °C (0 °F). The prechamber engine with glow plugs will start down to -25°C (-13 °F). In addition, cold start of the DI engine would be accompanied by white and blue smoke with higher odor intensity.

4. Exhaust Emissions
   HC, CO and NO_x are about two to three times higher as those of pre- and swirl chamber engines. This statement, of course, only refers to passenger car DI diesels with cylinder displacements of 0.5 to 0.6 liter. Larger cylinders as used in truck engines display more favorable values.

For these four main reasons application of the DI system to LDV diesels has hitherto not been meaningful, although lower fuel consumption continues to be a certain incentive.

The following results will, therefore, mainly refer to the PC-system, and comparisons to the SC-system shall be made.

Development of the Daimler-Benz Diesel Engine

Success of our high speed diesel in passenger cars began about 40 years ago, with the 260 D. In 1948, the 170 D was introduced parallel to the 1.7 ltr gasoline engine. Diesel and gasoline engines, even in those days, were manufactured on the same lines as they are today. Until 1967 only one diesel engine model was carried, improved throughout the years. Then, in quick succession further models were added to the 200 D: the 220 D, the 240 D, and the 300 D.

Demand has increased so notably that at present almost every second passenger car is powered by a diesel engine. This success can be traced back to a number of interesting characteristics:

1. low fuel consumption (even at low emission levels)
2. good driveability and smoothness
3. good dependability
4. acceptable noise level
5. low emissions

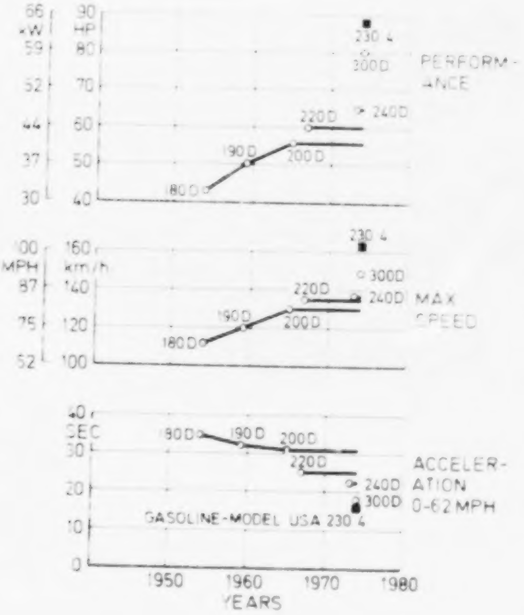


FIG. 3 - DEVELOPMENT OF MERCEDES-BENZ LDV-DIESEL-ENGINES

As can be seen in Fig.3, performance, starting in 1954 with the 200 D until today's 300 D, increased from 32 to 59 kW (43 - 80 HP) and maximum vehicle speed from 110 to 148 km/h (68 - 93 mph), in order to adapt the diesel vehicles to the growing needs of modern traffic. Acceleration simultaneously improved. Whereas the 180 D took about 35 sec. from Zero to 100 km/h (62 mph), the 300 D only takes about half the time and comes very close to our 4-cylinder U.S. gasoline model 230.4.

ITEM		200D	220D	240D	240D 3.0 (300D)
POWER	KW (BHP)	40 (55)	44 (60)	48 (65)	59 (80)
REVOLUTION	MIN^{-1}	4200	4200	4200	4000
BORE	MM	87.0	87.0	91.0	91.0
STROKE	MM	86.3	92.4	92.4	92.4
DISPLACEMENT	CM^3	1988	2197	2404	3005
MAX SPEED	KM/H (MPH)	130 (81)	135 (84)	138 (86)	148 (92)
REAR AXLE RATIO		392	392	369	346
WEIGHT	KP	193	195	203	234
SPECIFIC WEIGHT / POWER	KP/KW KP/BHP	4.8 (3.5)	4.4 (3.2)	4.2 (3.1)	4.0 (2.9)
0 -100 KM/H (0-62 MPH)	SEC	31.0	27.0	24.0	19.0

FIG. 4 - CHARACTERISTIC DATA OF MERCEDES-BENZ LDV WITH DIESEL-ENGINES

The 3 liter engine of the 300 D is the first 5-cylinder Diesel to be installed in a passenger car. As the major dimensions (bore, stroke, cylinder distance) are the same as in the 240 D engine a wide interchangeability of parts could be achieved. New is, in particular, the maintenance-free injection pump with mechanical governor, key operated starting system, and altitude correction. The engine carries a viscous fan, and the oil cooler is thermostat controlled. Dimensional details are listed in the table of Fig. 4.

Fuel Consumption

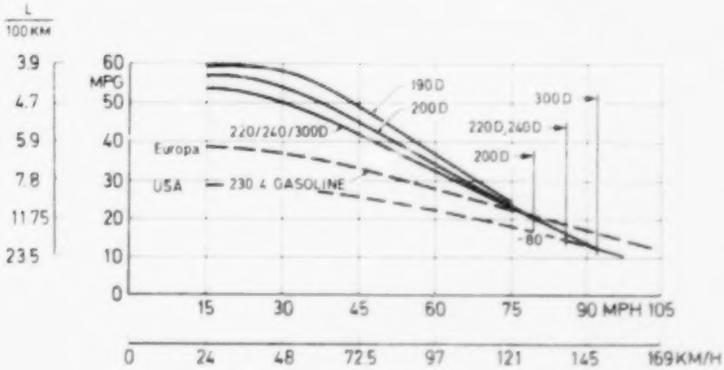


FIG. 5 - FUEL CONSUMPTION AT ROAD LOAD

By providing a more rear-axle ratio frequently driven part load conditions were shifted to regions with better specific fuel consumption, so that the consumptions of the 220 D, 240 D, and 300 D are about identical, Fig. 5, and all diesels are better than the gasoline 230.4, European version. The difference to the US-version, by the way, is much more pronounced. Only at speeds beyond 130 km/h (80 mph) is the gasoline model superior, a feature which cannot be utilized in average daily traffic. On the contrary, the superiority of the diesel engines in city traffic and below 100 km/h (60 mph) comes out clearly. This is verified by Fig. 6, which lists consumption results obtained in CVS tests by EPA. Fuel consumption of gasoline models varies between 10.5 and 20 MPG, that of the diesels between 24 and 25 MPG.

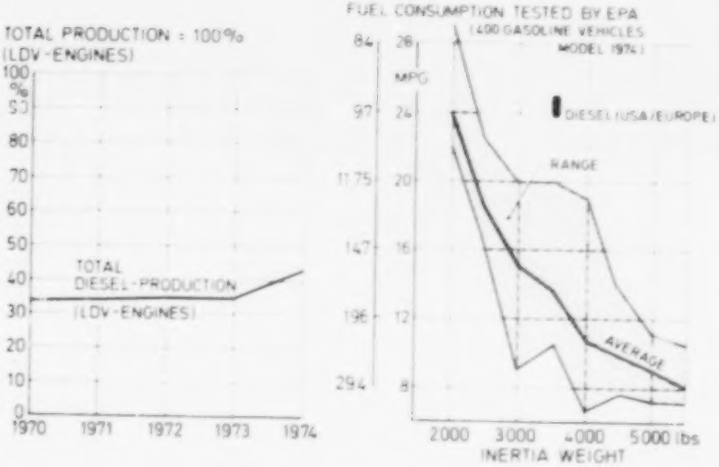


FIG. 6 - FUEL ECONOMY IN CVS-TEST

In comparing consumption of the PC and SC-system hardly any differences can be found in the lower speed range. A small advantage in fuel consumption can be noticed for the SC system only at high speeds and full load, it may become as large as 5 %. In the CVS test cycle there exist hardly any differences in consumption.

The closer one attempts to modify the combustion process of the SC system in the direction of a PC system (i.e. towards constant pressure combustion in order to realize a more quiet SC-engine) the more this consumption gap will narrow.

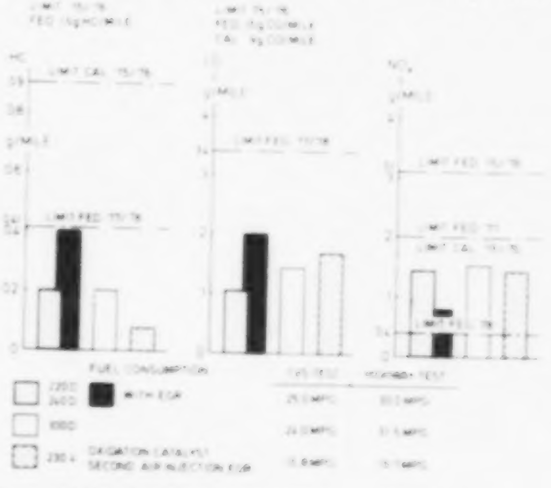


FIG. 7 - EMISSIONS CONTROL-SYSTEMS (CVS-TEST RESULTS) LDV-DIESEL- AND GASOLINE-ENGINES

Exhaust Emissions in CVS Test

Fig. 7 shows the

emissions of our PC diesel engines as measured in the CVS test procedure. The values are about half those of the US Standards for HC and CO in 1977. However, 0.4 g/mile of NO_x cannot be met, not even with EGR. If exhaust gas is recycled at a rate as high as 35 % it is possible to cut the NO_x emission in half, but HC and CO are doubled. On diesel engines NO_x reduction by means of catalysts is not possible.

As for the emissions of the SC-engine - not shown in the figure - its HC emissions are about twice as high, just at the level of the standard, and CO emissions are also higher, whereas NO_x is a little lower than in the PC engine.

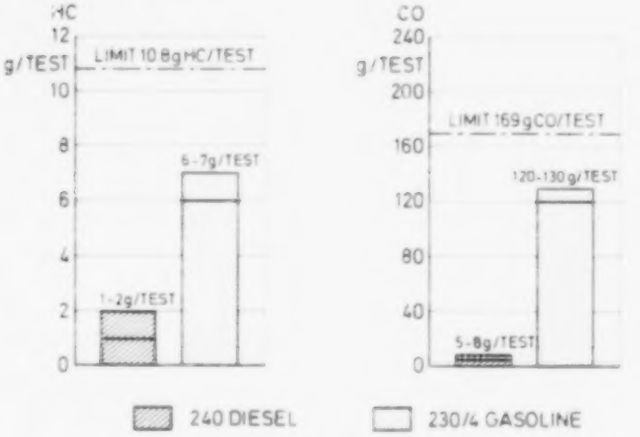


FIG. 8 - COMPARISON OF EMISSIONS (EUROPE-TEST RESULTS)

Emissions in European Cycle

Here, too, the diesel's emissions are definitely lower than those of gasoline engines, Fig.8. A diesel engine emits only about one tenth of CO and one quarter of HC. NO_x emissions, presently not limited in Europe, are about half those of gasoline engines.

Emissions in 13-Mode-Cycle

Since our LDV diesel engine is also installed into small pick-ups and is often used as a stationary engine, we also conducted emission tests following the stationary U.S. procedure - 13-mode-cycle - for vehicles of 10,000 lbs GVWR and over.

The results in Fig. 9 (please turn to next page) show the same tendency as in the case of cyclic tests. CO emissions are below the 1977 Standards by a clear margin. NO_x + HC emissions total to 5 gm/BHP · h. Also shown is the influence of avoiding the erratic late injection sometimes occuring at certain operating conditions and of EGR, both for the 2.4 liter engine.

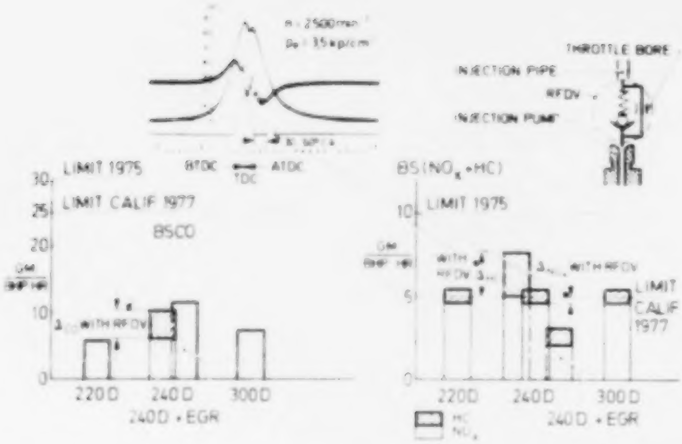


FIG. 9 - EMISSIONS CONTROL-SYSTEMS (13-MODE-TEST RESULTS) LDV-DIESEL-ENGINES

Emission of Smoke/Soot

The amount of emitted soot, Fig. 10, is very small, but due to the high rate of absorption of light quite noticeable. In a 2.4 liter engine it amounts to about 0.2 to 0.3 gm/mile. Our LDV diesels can meet the standards proposed in ECE Draft Regulation No. 24, as well as those for trucks in the U.S.

For high-altitude operation our LDV diesels possess a possibility for correction, so that these smoke regulations can also be met under altitude conditions.

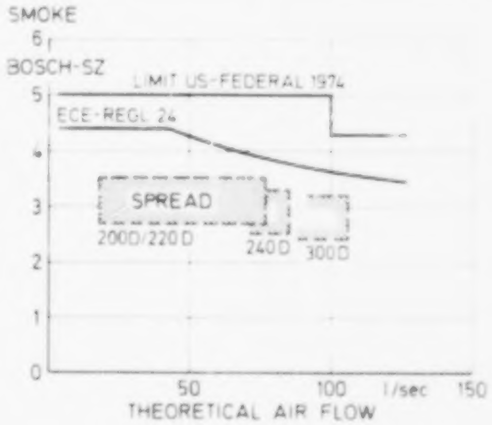


FIG. 10 - SMOKE AT FULL-LOAD

Emission of SO_2

Sulfate pollution is mentioned again and again in connection with diesel engines. It is known that diesel fuel has a varying sulfur content, in general 0.2 % - 0.4 %. From the standpoint of the diesel engine, the sulfur is undesirable because it increases cylinder and piston ring wear. In looking at the total SO_2 emissions in the Federal Republic of Germany, the main share (about 80 %) is contributed by industry and the rest almost totally by home heating. The share of diesel-fueled engines is only approximately 1 %. If all of the sulfur contained in diesel fuel, assuming a 0.5 % content, would be completely transformed into sulfur dioxide, our 240 D would emit 1.0 g/mile. According to the latest surveys only 50 - 60 % of the sulfur in the fuel, however, is transformed. A large share remains in the lubrication oil.

Noise

The PC combustion process with its pressure rise of only 2 bar/°CA and peak pressures of 60 to 65 bar, see Fig. 11, is of similar order of magnitude as in gasoline engines. This results in exterior and interior vehicle noise levels which throughout a wide range of operating conditions are hardly higher than those of gasoline engines. We believe that by selecting the PC system we have made a vital contribution to the environmental problem of noise.

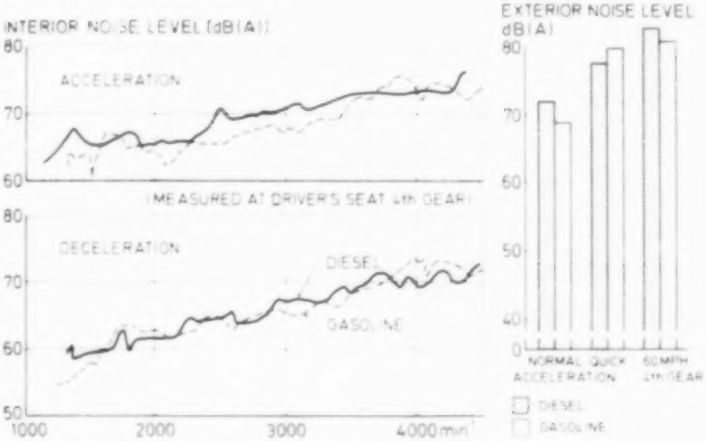


FIG. 11 - NOISE LEVEL

Summary

This presentation has attempted to show which criterions were taken into consideration in order to develop an optimal combustion system for all possible applications of high speed LDV diesels, and why the prechamber process represents the best compromise between excellent fuel economy, low emissions, and noise levels.

So far, great progress has been achieved. Further improvements will be made. One area of research is supercharging, Fig. 12. Specific fuel consumption at full load can be improved by 10 %, and together with a remarkable improvement of part load consumption performance can be stepped up by more than 40 %. Mr. Hiereth will cover this area in his presentation, which will, in particular, deal with the Comprex supercharger.

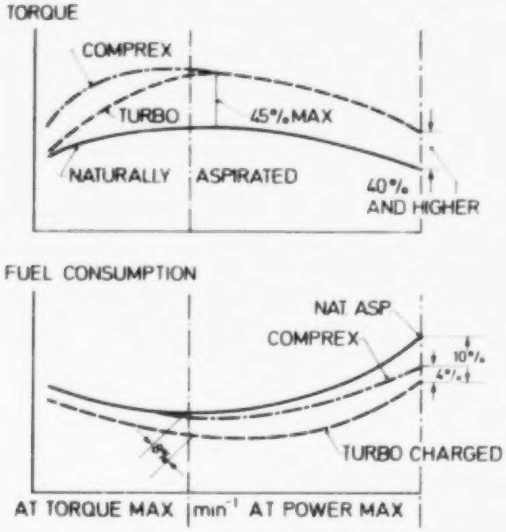


FIG. 12 - TURBOCHARGED MERCEDES-BENZ LDV-DIESEL-ENGINES

Whether supercharging will be employed on LDV diesels same as on large diesel engines, or whether further increases of displacement are more desirable, has yet to be determined.

This brief presentation hopes to have contributed to the insight into problems associated with the high speed diesel engine for passenger cars.

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Progress reports
on the
research and development projects
promoted by the
Federal Minister for Research and Technology

Rapports-bilan
relatifs aux projets de recherche
et développement encouragés par le
Ministre fédéral de la Recherche et de la Technologie

Statusberichte
über die vom
Bundesminister für Forschung und Technologie
geförderten Forschungs- und Entwicklungsvorhaben

As of: August 1974
Situation: Août 1974
Stand: August 1974

Rußreduzierung bei Dieselmotoren durch Abgasnachbehandlung.

Rußbeschaffenheit und meßtechnische Erfassung.

N. Metz, W. Müller

Daimler-Benz A.G., Stuttgart-Untertürkheim

The knowledge on composition, characterstics and origin of soot formation, as well as on soot quantity measurements and soot particle size distribution required to solve the problem of reducing soot emission of Diesel engines by afterburning is presented. Possible methods of afterburning are discussed and soot afterburning, using a regenerative heat exchanger, as the most promising method, is explained.This project,sponsored by the 'Bundesminister für Forschung und Technologie' was started at the end ef 1973.

On traite des connaissances sur la nature, les propriétés et la formation de la suie ainsi que sur la mesure quantitative de la suie et la répartition pa ordre de grandeur des particules de celle-ci, connaissances nécessaires pour résoudre le problème d'une réduction en aval du moteur de l'émission de suie sur les moteurs diesel. On évoque les possibilités d'un traitement ultérieur et on explique la combustion subséquente de la suie au moyen d'un échangeur de chaleur à régénération comme méthode ayant la plus grande chance de succès. Ce projet subventionné par le "Bundesminister für Forschung und Technologie" a été commencé fin 1973.

Die zur Lösung des Problems einer nachmotorischen Verminderung der Rußemission bei Dieselmotoren erforderlichen Kenntnisse über Beschaffenheit, Eigenschaften und Bildung des Rußes sowie die Messung von Rußmenge und Partikelgrößen-Verteilung werden dargestellt. Möglichkeiten zur Nachbehandlung werden erörtert und als aussichtsreichste Methode die Rußnachverbrennung mit Hilfe eines Regenerativ-Wärmetauschers erläutert. Das vom Bundesminister für Forschung und Technologie geförderte Vorhaben wurde Ende 1973 begonnen.

1. Beschaffenheit und Eigenschaften

Ruß, der als Schwarzrauch des schadstoffarmen Dieselmotors auftritt, ist nach röntgenspektroskopischen Untersuchungen [1] amorphe Kohle in Form von feinstverteiltem Graphit. Im Gegensatz zum Graphitgitter sind die molekularen Kohlestoff-Sechserringe des Rußes in Schichtanordnung unregelmäßig gegeneinander verschoben. Neben dem weitaus überwiegenden Anteil, dem elementaren Kohlenstoff, enthalten alle Ruße noch bis zu 1% Wasserstoff, Sauerstoff und oft auch etwas Schwefel. Es ist wegen der starken Koagulationsneigung des Kohlenstoffs nicht möglich, von einer bestimmten Teilchengröße zu sprechen. Die kleinsten auf Elektronenmikroskopaufnahmen noch erkennbaren Teilchen sind Kristalle von nahezu kugeliger Form mit einem Durchmesser um 5 nm. Bild 1 zeigt, dass diese Teilchen lockere, dreidimensional verzweigte Ketten unterschiedlicher Dichte bilden.

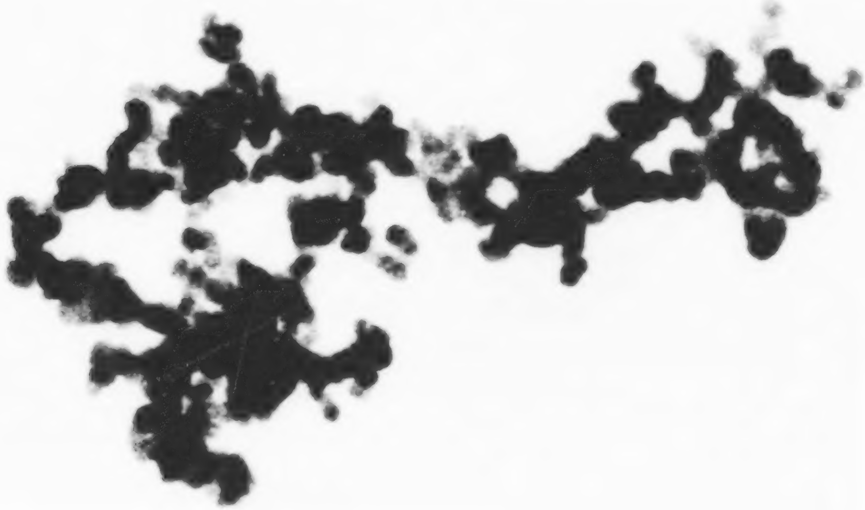

Bild 1 Rußkoagulate, aufgenommen mit einem Elektronenmikroskop. Vergrösserung 108 000-fach.

Diese Ketten wiederum verbinden sich je nach Druck und Temperatur zu lockeren Rußkoagulaten, deren Größe von 10nm bis in Einzelfällen zu ca. 50µm mit einem Verteilungs-Maximum unter 0,1µm reicht.

Je höher die Temperatur bei der Rußbildung ist, desto größer werden die Ausgangskristalle und desto mehr gleicht die Orientierung der Gitterebenen dem natürlichen Graphit.

Von überragender Bedeutung ist in diesem Zusammenhang die

Eigenschaft des Kohlenstoffs, als einziges Element durch Einfach- Doppel- oder Dreifachbindungen mit sich selbst Ketten und Ringe von beliebiger Länge und Anordnung zu bilden.

Die technologischen Eigenschaften des Rußes hängen weitgehend von der Teilchengröße ab. Im Wasser ist Ruß völlig unlöslich. Auch von Chemikalien wird Ruß kaum angegriffen. Die Dichte des Rußes liegt zwischen 1,7 und 1,9 g/cm^3. Die Verbrennungswärme bei einer Dichte von 1,845 g/cm^3 beträgt 34,2 kJ/g. Die Entzündungstemperatur liegt zwischen 370 und 440°C. Unabhängig von der jeweils vorliegenden Modifikation ist der Kohlenstoff ein geschmack- und geruchloser Stoff, der erst bei 3700°C schmilzt und bei 3850°C siedet.

2. Rußentstehung

Über die Rußentstehung liegen verschiedene Hypothesen vor [2] bis [7], genaue Einzelheiten über den chemischen Reaktionsablauf sind aber noch ungeklärt.

Ruß von Diffusionsflammen und Dieselabgasruß werden in den meisten diesbezüglichen Arbeiten aufgrund des gleichartigen Aussehens unter dem Elektronenmiskroskop als identisch angesehen.

Beim Dieselmotor treten nach der Zündung ähnlich hohe Temperaturen wie in Diffusionsflammen auf. Während der Verbrennung kommt es zu einer Pyrolyse, d.h. einem Cracken der vorwiegend paraffinischen Kohlenwasserstoffe des Dieselkraftstoffs. Dieses Aufbrechen der zwischen 12 und 22 Kohlenstoffatome enthaltenden Kohlenwasserstoffketten des Ausgangskraftstoffs führt zu wiederholten Doppelbindungen zwischen den C-Atomen der gespaltenen Restketten. Dabei entstehen im einfachsten Fall der Äthylen- bzw. Äthan-Diffusionsflamme zunächst Äthylen ($H_2C{=}CH_2$), dann Acetylen ($HC{\equiv}CH$) und Butadien ($H_2C{=}CH{-}CH{=}CH_2$), und über die Bildung von Vinylacetylen ($HC{\equiv}C{-}CH{=}CH_2$) und Diacetylen ($HC{\equiv}C{-}C{\equiv}CH$) Polyacetylene und dabei Dreifachbindungen zwischen den C-Atomen. Die während des Crack-Prozesses entstandenen und daher bereits weitgehend wasserstoffarmen Kohlenwasserstoffverbindungen bilden unter dem dehydrierenden Einfluß der hohen Brennzonen-Temperaturen von über 1000°C ringförmige, dem Graphitgitter sehr ähnliche molekulare C-Strukturen.

Im Dieselmotor geschieht die Rußbildung und die Rußverbrennung weitgehend gleichzeitig, wobei aber während der Wärmefreisetzung die Rußbildung quantitativ schneller abläuft als die Rußverbrennung. Während die Rußbildung mit dem Ende der Wärmefrei -

setzung im Brennraum beendet ist, erfolgt über diesen Zeitpunkt hinaus solange noch eine weitere innermotorische Nachverbrennung des Rußes, als die Brenntemperatur und der Sauerstoffgehalt ausreichend hoch sind. Der Rußbildungsprozeß und die sofort einsetzende Koagulation des Rußes verlaufen extrem rasch. So ist die Bildung der Rußkoagulate z.B. bei 2700 /min nach 3 ms, bei 2000/min nach 5 ms und bei 1100 /min nach 10 ms abgeschlossen, was etwa 50^o Kurbelwinkel entspricht.

Die Rußkonzentration des Abgases wird daher vor allem durch die Rußbildungsvorgänge beim Verbrennen im Zylinder bestimmt und weniger durch die parallel anlaufende Rußverbrennung der entstandenen lockeren Rußkoagulate beeinflußt. Die für das Auftreten der ersten Rußpartikel erforderliche Zeit ist nach Beobachtungen mit der Hochgeschwindigkeitsflammenfotografie [8] mit 0,1 ms außerordentlich kurz.

Die im Dieselmotor entstehenden Rußmengen sind neben einer Vielzahl von Einflußgrössen, wie Einspritzbeginn, Einspritzgesetz, Ablauf der Gemischbildung stark abhängig von der Art des Verbrennungsverfahrens (Vorkammer, Wirbelkammer, Direkteinspritzung), von der Motordrehzahl, vor allem aber von der Last. Die Rußmengen bei PKW-Dieselmotoren liegen zwischen etwa 10 und 70 g/h.

3. Meßtechnische Erfassung

Die beiden wichtigsten Meßgrößen für eine Beurteilung von Maßnahmen zur Reduzierung des Rußes sind das bezogene Rußgewicht in g/Nm^3, g/h, g/PSh bzw. g/kWh und die Größenverteilung der Rußkoagulate.

Aussagen über die Rußmenge können mit bedingter Genauigkeit mit indirekten Schnellmeßverfahren [13] wie Bosch-Filter-Reflektionsmessung, Hartridge-Rauchmeter, USPHS- und Beckmann-Rauchgasmesser, von Brand- und Mobil-Rauchgasmesser, Bosch-90^o-Dispersionsmeter, Caterpillar- und Ethyl-Rußkonzentrationsmeßmethode erreicht werden, wobei in der BRD die ersten zwei erwähnten Methoden gebräuchlich sind. Die Vielzahl der vorhandenen Methoden zeigt an, dass keine der Lösungen voll befriedigt. Die direkte Erfassung der Rußmenge des gesamten Abgasstromes mit einem Filter wäre aufgrund der hohen durchgesetzten Gasvolumina höchstens im unteren Drehzahlbereich möglich.

Zur Erfassung der Partikelgrößenverteilung sind bis jetzt nur diskontinuierlich arbeitende Verfahren, wie der Andersen Kaskadenimpaktor, der Stöberrotor oder der Mikrovideomat von Zeiss geeignet.

3.1 Probenahme

Voraussetzung für die Auswertung der beiden genannten Meßgrößen ist eine genaue und reproduzierbare Probenahme. So muß der Probenahmeort für die Bewertung von Rußreduzierungsmaßnahmen am Auspuffende sein, die Probenahmetemperatur über dem Taupunkt liegen, um Fehler durch Kondensation auszuschließen, die statistisch bedingte Anzahl der Messungen zwischen 10 und 15 liegen und das Rußprobengewicht für gravimetrische Auswertungen mindestens 10 mal so hoch wie die Empfindlichkeit der Mikrowaage sein.
Fehler durch eine nichtisokinetische Entnahme werden mit abnehmendem Partikeldurchmesser kleiner und können unter 3 µm, wie es beim Dieselruß der Fall ist, vernachlässigt werden [9] . Der Probentransport vom Ort der Probenahme (Prüfstand) zum Ort der Auswertung (Labor) muß in Exsikkatoren erfolgen.

3.2 Auswertung

Während zur Grobüberüberprüfung einer Rußverminderungsmaßnahme die Messung nach Bosch ausreicht, sind zur genauen Untersuchung der Wirksamkeit bzw. schon für die Auswahl von Nachbehandlungseinrichtungen die nachfolgend genannten Meßmethoden notwendig.

Die gravimetrische Auswertung der auf Filtern gesammelten Rußpartikel erfolgt entweder als Gesamtgewicht oder bereits nach Größenklassen verteilt durch eine elektronische Mikrowaage mit einer Genauigkeit von 10 µg.
Die mikroskopische Auswertung kann mit dem Mikrovideomat von Zeiss erfolgen, d.h. mit einem Mikroskop mit angeschlossener Fernsehkamera und einer Elektronik, welche die von der Kamera empfangenen Impulse nach Partikelzahl, Projektionsfläche und Partikeldurchmesser größenverteilt auswertet.
Eine Schwierigkeit bei diesem Meßverfahren ist die starke Koagulationseigenschaft der Rußpartikel, die eine vorangehende Präparation erfordert. Diese wurde so ausgearbeitet, daß die Rußschicht von einem Membranfilter abgekratzt wird, in verschiedenen Lösungsmitteln zwischen 2 und 5 Minuten ultrabeschallt wird, wobei sich Äthanol als geeignetes Lösungsmittel erwies.

Allerdings muß die Identität der bei der Ultraschallbehandlung entstandenen Partikelgrößen mit den ursprünglich im Abgasstrom vorliegenden Partikelgrößen noch bewiesen werden.
Nach ausreichender Erfahrung über Rußmenge und Partikelgrößenverteilung im Dieselmotorenabgas kann über den möglichen Einsatz von kontinuierlich anzeigenden Geräten entschieden werden.

4. Maßnahmen zur Rußreduzierung nach dem Motor

Zur Verminderung des bei der dieselmotorischen Verbrennung entstandenen Rußes kommen grundsätzlich sowohl reine Rückhalte- und Nachverbrennungssysteme als auch deren Kombinationen infrage.

4.1 Filterung

Bei der Filterung bestehen die zu lösenden Hauptprobleme in der relativ großen anfallenden Rußmenge und der geringen Teilchengröße von unter 0,1 µm der Hauptrußmenge. Erste Versuche zeigten, daß ein brauchbarer Abscheidegrad nur über kleine Porenweiten zu erzielen ist, die bei in Fahrzeugen möglichen Filterdimensionen einen hohen Druckverlust bei hohen Motordrehzahlen verursachen würde. Die Rußaufnahme des Filters ist, bei gegebener Geometrie, wegen des noch weiter ansteigenden Druckverlustes begrenzt. Intermittierend arbeitende Abbrennverfahren am eingebauten Filter oder kurze Wartungsintervalle wären deshalb erforderlich.

Elektrostatisch arbeitende Filter, die wegen ihres hohen Abscheidegrades bei großer Rußaufnahme und geringem Druckverlust interessant wären, sind in ihrem gegenwärtigen Entwicklungsstadium wegen zu großem Platz- und Energiebedarf im Fahrzeug nicht brauchbar.

4.2 Nachverbrennung

Mit einem thermischen Reaktor kann der im Abgas schwebende Ruß kontinuierlich nachverbrannt werden. Die hierbei auftretenden Probleme bestehen darin, daß wegen der chemisch trägen teilkristallinen Struktur der Rußpartikel entweder lange Verweilzeiten im Reaktor oder aber Gastemperaturen erforderlich werden, die erheblich über den auftretenden maximalen Abgastemperaturen liegen müssten. Eine ständige Wärmezufuhr zum Erreichen einer ausreichend hohen Temperatur mittels Kraftstoffverbrennung würde eine wesentliche Erhöhung des Kraftstoffverbrauches bedeuten.
Zur Senkung des Kraftstoffverbrauches gegenüber dem kraftstoff-

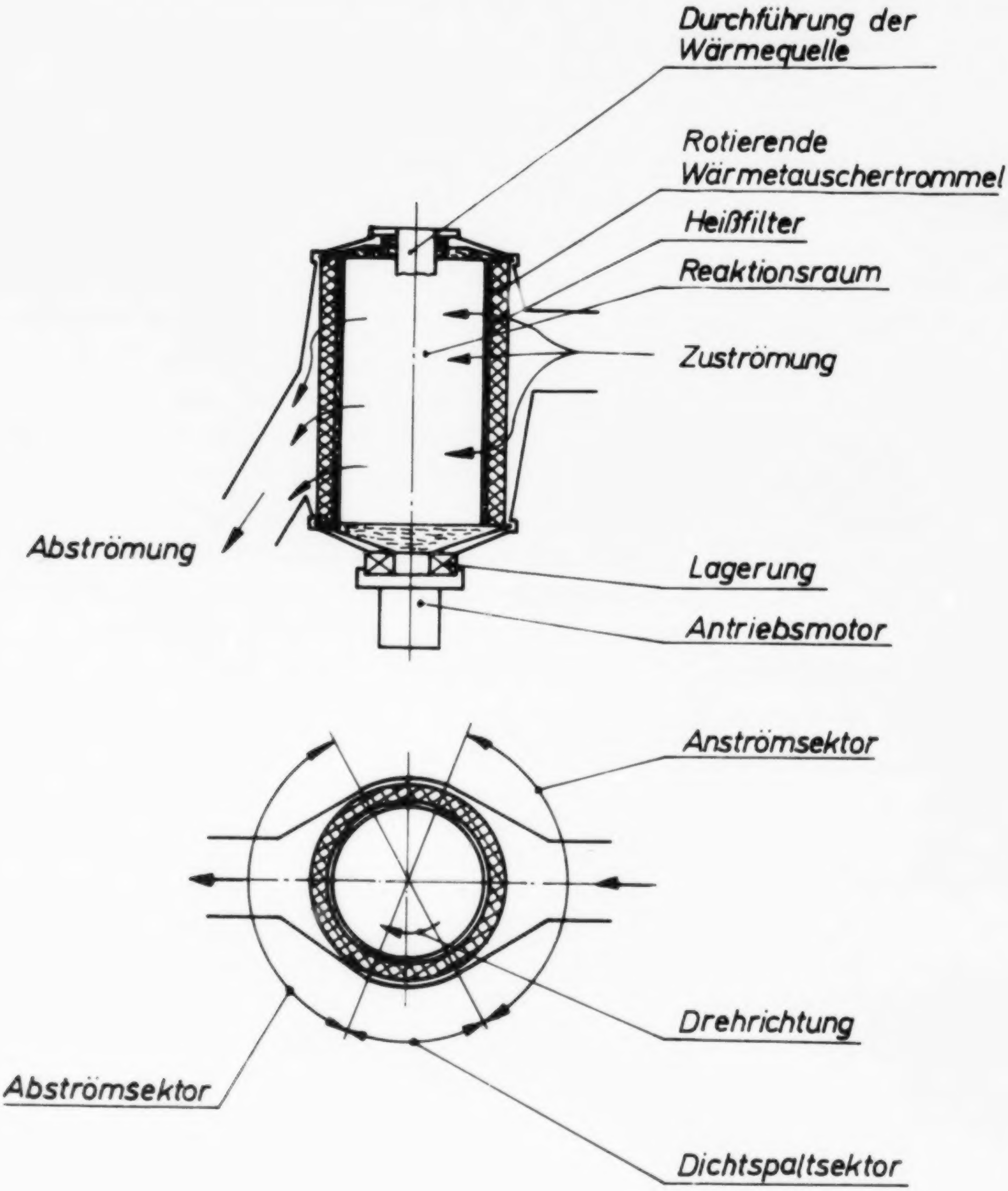

Bild 2
Prinzipskizze einer Regenerator-Heißfilter-Kombination

beheizten Reaktor wurde ein Verfahren gefunden, das mit regenerativem Wärmeaustausch arbeitet. Da diese Methode, verglichen mit den vorstehend diskutierten Rückhaltesystemen, im gegenwärtigen Entwicklungsstadium den Vorteil bietet, daß sie bereits einen gangbaren Lösungsweg darstellt, wird z.Z. bevorzugt an ihrer Verwirklichung gearbeitet; sie soll deshalb etwas näher beschrieben werden.

4.3 Nachverbrennung mittels einer Regenerator- Reaktor- Heißfilterkombination

Der Regenerativreaktor besteht im Prinzip, wie aus Bild 2 ersichtlich, aus einem trommelförmigen rotierenden Regenerativ-Wärmetauscher, dessen Innenraum als Reaktionsgefäß dient. Er wird möglichst nahe am Motor direkt im Abgasstrom angeordnet. Mittels einer zusätzlichen Wärmequelle wird beim Anlassen des Motors dem Regenerator eine der notwendigen Abgastemperaturerhöhung entsprechende Wärmemenge zugeführt und gespeichert. Der Regenerator überträgt dann jeweils einem zuströmenden Abgasvolumen diese Wärmemenge und nimmt beim Ausströmen dieses Volumenteils annähernd die gleiche Wärme wieder auf, so daß das Abgas etwa mit der gleichen Temperatur, wie am Motoraustritt, den Reaktor verläßt. Dieser Vorgang erfolgt, wie vom Gasturbinenwärmetauscher her bekannt, kontinuierlich, sofern die Wärmetausch- und Wandwärmeverluste ständig im Reaktor durch eine besondere Zuführung ersetzt werden. Die Eigenschaft des Regenerators, einen Wärmeaustauschwirkungsgrad von weit über 90% zu ermöglichen, bietet die Voraussetzung für noch erträgliche Gesamtverluste beim Motorbetrieb.

Über die Oxidationsbedingungen für den Dieselruß liegen noch keine ausreichenden Untersuchungen vor. Aus den bisher verfügbaren ersten Versuchsergebnissen und anhand von Literaturangaben [15] läßt sich aber jetzt schon sagen, daß es zweckmässig ist, zur Begrenzung von Reaktortemperatur und -volumen einen Heißfilter vorzusehen, der die Aufgabe hat, die Verweilzeit der größeren Rußpartikel zu erhöhen.

Die Arbeiten am Regenerativ-Reaktor befinden sich im Stadium der konstruktiven Überlegungen. Die zu überwindenden Schwierigkeiten werden, im Unterschied zum bekannten Thermo-Reaktor für den Ottomotor, in der Beherrschung der voraussichtlich noch höheren Temperaturen und der Durchführung und Regelung der Wärmezuführung für Start und Betrieb liegen. Er bietet jedoch gegenüber den reinen Filtermethoden, gerade wegen der für die Rußverbrennung erforderlichen hohen Temperaturen die Voraussetzung, daß mit hoher Wahrscheinlichkeit alle übrigen brennbaren Abgasinhalts- und Geruchsstoffe, auch im Teillastgebiet des Motors, nachverbrannt werden.

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DISCHARGE PHENOMENA IN SPARK PLUGS

H. ALBRECHT, W. H. BLOSS, R. MALY, B. SAGGAU and E. WAGNER
Institut fuer Physikalische Elektronik, Universitaet Stuttgart,
D-7000 Stuttgart 1, Boeblinger Str. 70, FRG.

The incipient stages of sparks in spark plugs have been investigated both electrically and spectroscopically (0 - 200 ns). Very high carrier densities (5 x 10^{18} cm^{-3}) and gas temperatures of 3000 K have been measured as early as 10 - 20 ns after spark onset. Molecules as N_2 are already fully dissociated at that time, the electrically supplied energy being stored as potential energy in ionized and dissociated molecules. From these sources energy is liberated very slowly in intervals of up to several microseconds.

Nous avons analysés les caracteristiques électriques et spectroscopiques d'étincelles de bougies dans leurs phases initiales (0 - 200 ns) et nous pouvions constater une très grande densité des électrons (5 x 10^{18} cm^{-3}) et de hautes températures de gaz (3000 K) 10 - 20 ns après le début de l'étincelle. A cette periode les molécules - comme N_2 - sont déjà entièrement dissociées. De l'énergie électrique il result un dépot d'énergie potentielle en forme de molécules ionisées et dissociées qui ne se libre que très lentement (quelque µs).

Die Anfangsstadien von Funkenentladungen in Zündkerzen wurden elektrisch und spektroskopisch untersucht (0 - 200 ns). Es ergaben sich sehr hohe Trägerdichten (5 x 10^{18} cm^{-3}) und Gastemperaturen (3000 K) bereits 10 - 20 ns nach Funkenbeginn. Moleküle wie N_2 sind zu diesem Zeitpunkt bereits völlig dissoziiert. Die zugeführte elektrische Energie wird als potentielle Energie in Form von ionisierten und dissoziierten Molekülen gespeichert. Daraus wird die Energie nur sehr langsam wieder freigesetzt (bis zu µs).

Though electric sparks are known to efficiently ignite proper fuel-air mixtures in internal combustion engines /1/, little is known yet about most of the physical and chemical reactions actually involved. If these reactions were fully known, more efficient ignition systems could be designed according to demands as: effective emission control, optimization of fuel economy, reliable ignition of poorlymixed and extremely lean mixtures, new fuels, etc. There is no doubt however, that processes other than pure thermochemical reactions such as excitation, ionization, dissociation, emission and absorption of electromagnetic radiation play a significant role at least in the very early stages of the ignition process /2/.

Our investigations therefore concentrate on these processes, requiring new experimental and theoretical approaches. Since very fast changes in voltage and current occur, ranging from ns to ms, experimental setups have to be designed according to U.H.F.-requirements. In Fig. 1 an example of an approved setup is shown /3,4/ for accurate measurements of both voltage- and current-

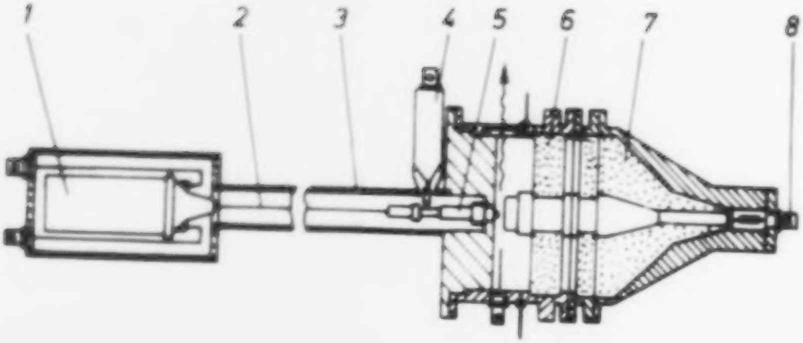

Fig. 1: Crossectional view of a setup for precise measurements of current and voltage of sparks by commercial ignition systems. 1: ignition coil, 2: high voltage cable, 3: brass shielding, 4: high voltage probe, 5: spark plug, 6: spark chamber /4/, 7: current shunt /4/, 8: spark current.

characteristics of sparks even in the ns-range. A comparison of modern ignition systems (a transistorized ignition system - TSZ - representing the conventional coil ignition system as well, and a capacitive discharge ignition system - HKZ -) driving a conventional spark plug in the very same way as in an Otto-engine, indicate, that these characteristics do not differ essentially unless about 200 ns after onset of the spark, Fig. 2 and Fig. 3 /5/. Up to that time, the curves are independent of the actual ignition system and are determined solely by the components of the external circuits

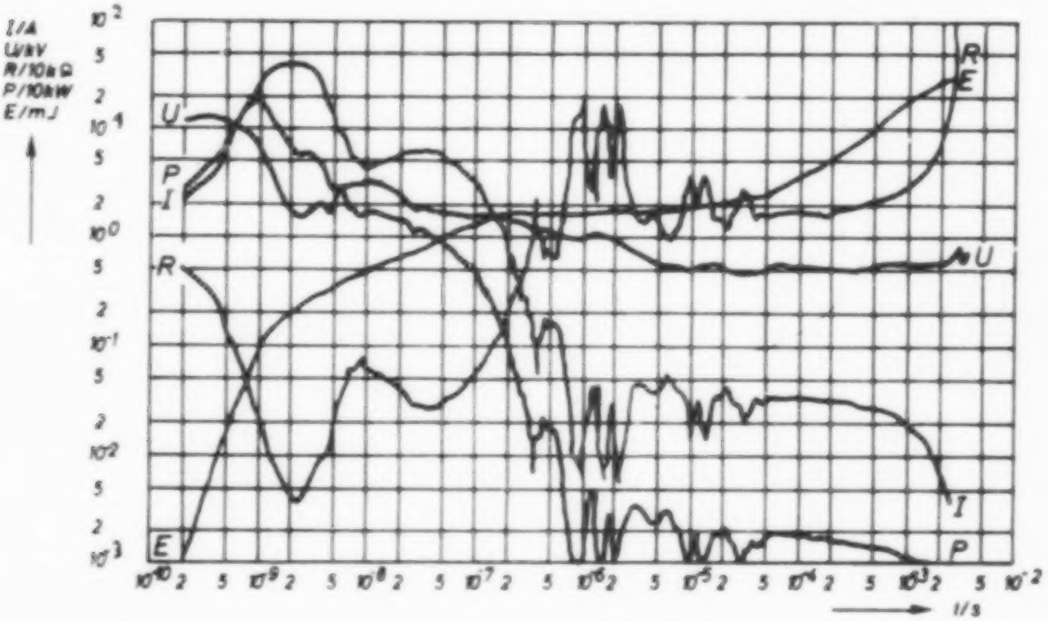

Fig. 2: Electrical characteristics of a transistorized ignition system - TSZ -. Discharge in air at 3 atmospheres. Electrode gap: 0.7 mm. The symbols are: U: spark voltage, I: spark current, R: spark resistance, P: power, E: energy input.

(capacitance and characteristic impedance of spark plug, high voltage cable and damping resistor) and the gas parameters (composition, pressure). Henceforth the TSZ due to its high internal impedance gradually forces the initial spark discharge into the well known low current glow discharge at almost constant voltage persisting until the energy supply is exhausted after a few ms.

The HKZ system on the other hand offers a sufficiently low internal resistance to change the initial spark mode temporarily into an arc discharge with nearly constant current at voltages as low as 30 V. Due to the higher resonance frequency of the HKZ system, there is a sign reversal in the voltage- and current-curves at roughly 20 µs. Thereafter a glow discharge developes identical to the TSZ except for its appreciably shorter duration (some hundreds of µs).

From a physical point of view it should be noted therefore, that 3 distinct discharge phenomena may be found in ignition systems,

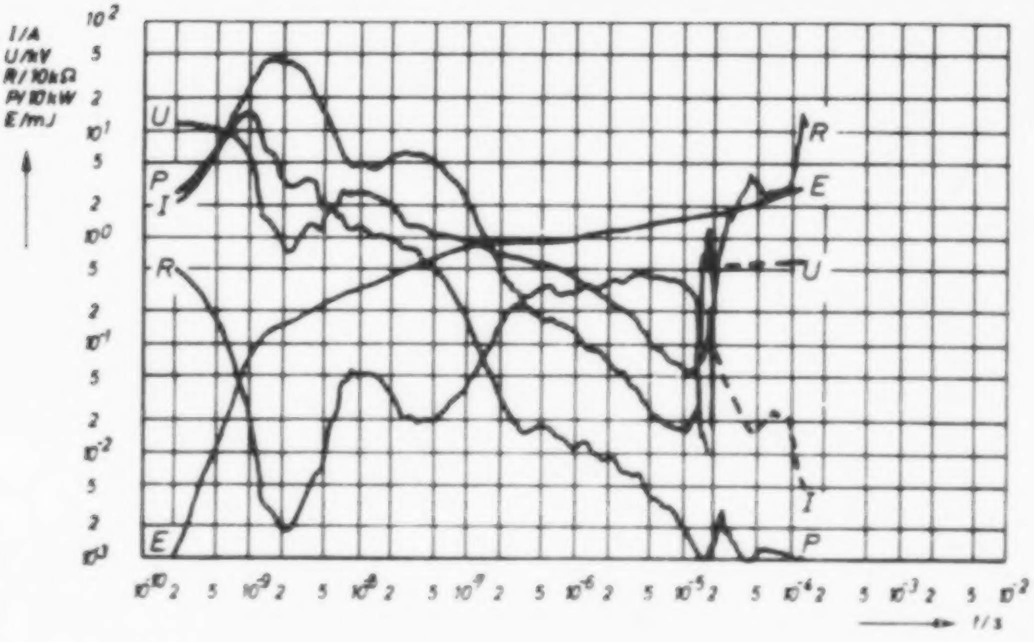

Fig. 3: Electrical characteristics of a capacitive discharge ignition system - HKZ -. Discharge in air at 3 atmospheres. Electrode gap: 0.7 mm. The symbols are: U: spark voltage, I: spark current, R: spark resistance, P: power, E: energy input, Dashed: reversed polarity of voltage and current.

each having its individual characteristics of energy transfer :

1. An initial high current spark mode persisting for a few 100 ns with a current ranging from 1 to several tens of an Ampere at voltages from 1 kV to some 10 kV. The power input is extremely high and may take values up to several hundreds of kW, whereas the total energy input amounts to tenths of mJ only.
2. A medium current arc discharge ca. 20 us in duration with almost constant current of some hundreds of mA and a voltage falling from a high 1 kV to as low as 30 V. The power input is orders of magnitudes lower, dropping to the Watt-range. The total energy input is comparable to the value in the spark mode of tenths of mJ.
3. A low current glow discharge at roughly constant voltage of 500 V, the current decreasing from 100 mA to zero. The power input is negligeably small whereas the energy input frequently amounts to some tens of mJ due to its long duration.

There is no doubt however, that the high current spark discharge is the most important with respect to efficient ignition. Otto-engines have been run successfully by this type of discharge exclusively /7,8/, and there is plenty of other experimental evidence, that the energy liberated in the high current spark mode is in good aggreement with the low minimum ignition energy of some tenths of mJ required for stoichiometric mixtures/9.

By suitable modern techniques this extremely short phase may be investigated in detail both electrically and spectroscopically as the authors have shown /5,6/. Theoretical and experimental work on the incipient current rise of sparks in N_2 and O_2 indicate, that the built-up stage may be adequately described by an avalanche process of electrons if the accumulating space charge and its feedback on the acting field is accounted for. Owing to different ionization- and attachment-coefficients the current rise time varies markedly with gas composition, being lowest for pure O_2. At atmospheric pressure rise times of 2 ns for N_2 and less than 0.5 ns for O_2 have been measured at electrode gaps of 0.5 to 1 mm, showing a strong tendency to decrease with pressure.

The kinetic energy gained by the electrons in the electric field is passed on to the gas molecules by excitation ionization and dissociation in the spark channel. So the current rise is accompanied by an increasing electromagnetic radiation allowing for spectroscopic analyses of the processes to follow.

Though most spectroscopic methods for investigations of a plasma are based on the existence of a thermodynamical equilibrium, which in our case cannot be assumed a priori, some useful techniques have been applied by the authors to extract desirable information on the short built-up phase from spectroscopic data.

A very fundamental quantity of a gaseous discharge is the carrier density. By doping the working gas with a small amount of H_2 - usually some 1 to 10 % in volume - the carrier density can be determined from the broadening of the Hα-line due to the Stark-effect. If the H_2-content is small the line broadening is due almost exclusively to the electrical micro-field of charge carriers from the working gas. Thus the determination of the carrier density of a H_2-doped plasma will be reduced to a simple comparison of the experimental Hα-line profile with a known theoretical master curve /6/. Carrier densities in arbitrary gases may thus be measured independently from thermal equilibrium of the plasma. As most fuels contain hydrocarbons from which atomic hydrogen is liberated by dissociation, this method may be ideally suited for investigations of the combustion process itself as well.

The method has been applied to sparks in N_2 obtained by a cable discharge. The current-voltage characteristic is very similar to the high current spark discharge in conventional ignition systems. The results for typical current pulses (≈40 A, 100 ns) are presented in Fig. 4. There is a rapid rise in electron density during the first 20 ns of the spark, when the external field is still high enough for efficient carrier production. The subsequently decreasing field - proportional to the spark voltage - and the increase in volume by channel expansion counteract a further increase however. Nevertheless a remarkably high maximum value of carrier density (several 10^{18} cm^{-3}) will be attained, decreasing only slowly in intervals up to some µs! Even several µs after the spark current has ceased an appreciable carrier density can be observed since possible loss mechanisms involve comparatively slow processes such as diffusion and recombination. A striking feature is however, that it is possible to detect a Hα-radiation at these late intervals at all. The life time of a Hα level is as short as ≈10 ns. Thus this intense line radiation long after current cease

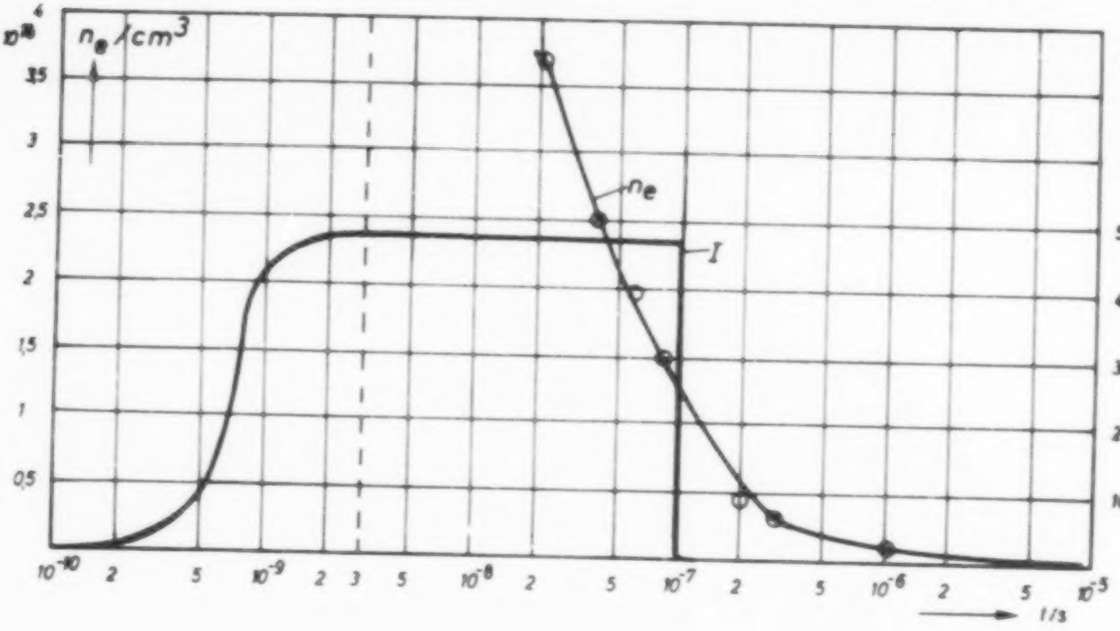

Fig. 4: Electron density n_e of a spark plasma obtained by a cable discharge. Spark current I is shown for comparison. Working gas: N_2 at 1 atmosphere doped with 8 % H_2 in volume. Electrode gap: 1 mm.

is a strong indication for a slowly decaying energy liberation from potential energy sources such as ionized and dissociated molecules generated during the first few ns of the spark. Moreover, as the excitation potential of H_{α} amounts to 12.1 eV, the liberated energy must be of the same order of magnitude! This shines new light on processes actually effecting ignition as well on the understanding of the induction periods found in ignition processes of most combustibles.

For carrier densities as high as some 10^{18} cm^{-3} one expects thermal equilibrium to be established rather quickly. Checks performed by the two line method for the determination of electron temperatures ($H\alpha$, $H\beta$) indicate indeed, that there is an incipient population inversion decaying during the first 20 to 40 ns. Henceforth however, normal population (Boltzmann statistics) is reestablishing. The electron temperature attains approximately 4000 K, a quite reasonable value, remaining fairly constant throughout the rest of the current pulse. Therefore, we may safely assume, that at least the velocity distribution of electrons corresponds to thermal equilibrium at intervals later than 60 ns from spark onset. Nevertheless, further evidence is required for the heavier particles such as atoms, ions and molecules.

The temperature of the neutral gas particles would provide a useful indication. Thus additional information could be obtained on the probability of ignition by pure thermochemical processes as well. Unfortunately this temperature cannot be measured directly during these extremely short time intervals involved.

By collision of the heavier particles of the plasma vibrational and rotational oscillations of the atoms will be excited in diatomic molecules as N_2 and O_2. Due to these oscillations the electric energy levels of the ground state of molecules will split into a number of vibrational and rotational levels. It is possible therefore, to deduce a vibrational or rotational energy and hence temperature from the analysis of molecular spectra. These temperatures are almost identical with the commonly termed "gas temperature" as the atoms as heavy particles will exchange energy by very few collisions due to their comparable masses.

Spectra taken on the cable discharge system as well as those on the commercial ignition systems reveal, that the vibrational and rotational band systems of the N_2-molecule (N_2^*) appear readily with the onset of the spark. In fact molecular radiation dominates the spectrum in the very early stage of the discharge. In Fig. 5 the proper spectral interval is presented, taken 5 ns after spark onset. It is remarkable however, that the bandsystems weaken already considerably during the first 10 to 20 ns, indicating an unexpectedly fast and efficient dissociation of the N_2 molecules by collisions with electrons being still highly energetic at that stage of the spark development. Thus it must be assumed, that this burst of molecular radiation is directly correlated to the formation of the spark channel. With a loss in spectral resolution the molecular bands can be found at all stages of the spark, even in the far ms-range of the glow discharge phase of coil ignition systems. This less intense radiation however, is most likely to be emitted from the boundary regions of the spark channel instead.

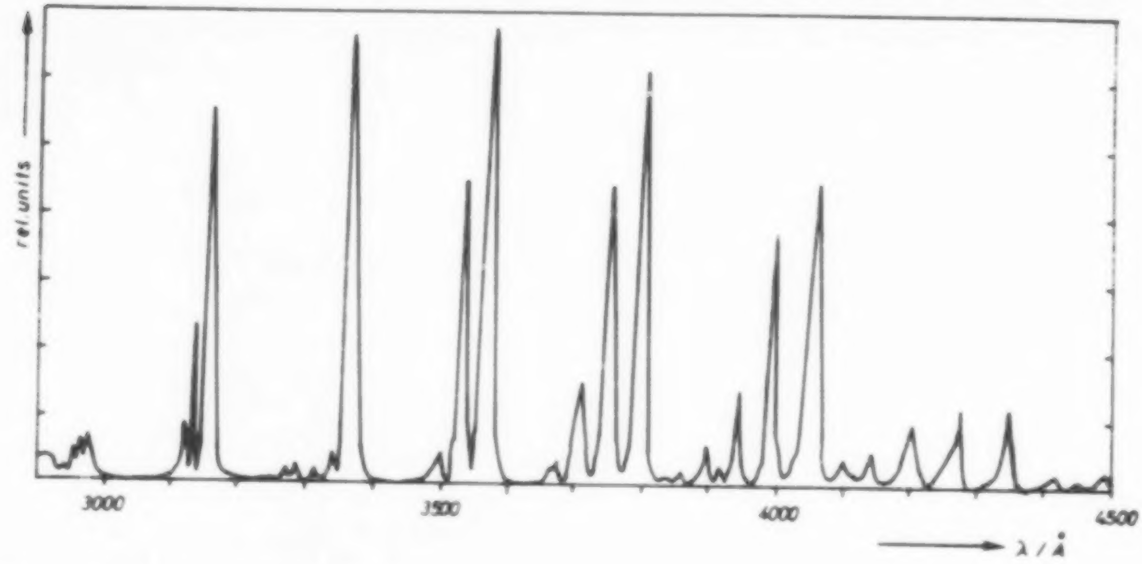

Fig. 5: Vibrational and rotational band systems of the 2nd positive system of the N_2 molecule. The spectrum was taken 5 ns after spark onset for the current pulse shown in Fig. 4.

The vibrational temperature evaluated for the first 50 ns of a spark from a commercial ignition system is given in Fig. 6. Below 3 ns no accurate evaluation of spectroscopic data is possible, as the photomultiplier used is not fast enough (rise time ≈ 3 ns) to give reliable results for the very steep rise in molecular radiation at current onset /6/. Within experimental error of an estimated 10 % the temperature of the spark plasma is constant during the first 50 ns of the spark and amounts to 3000 K. This extraordinary rapid rise in temperature to a level exceeding both thermal ignition temperatures and flame temperatures of almost all combustibles by far /1/, gives a good indication of the extreme conditions in the incipient stage of the spark.

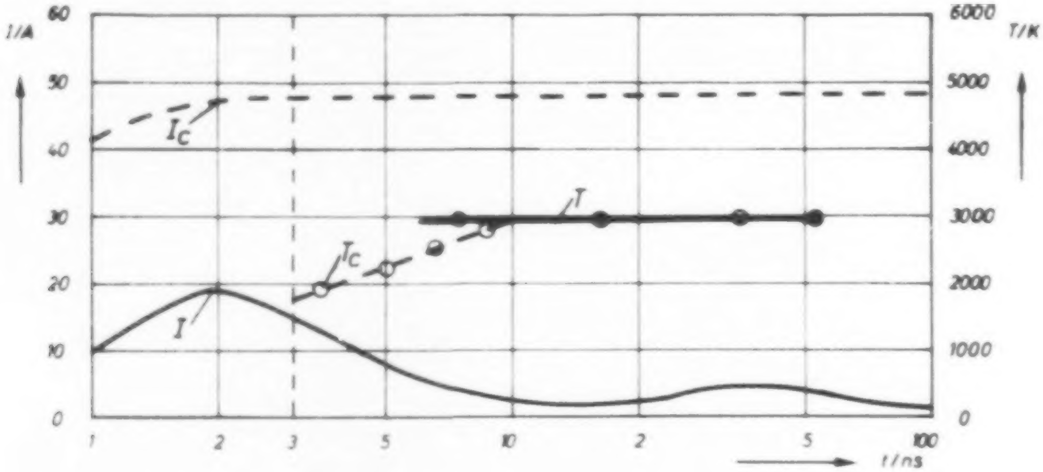

Fig. 6: Vibrational temperature T and T_c evaluated for a HKZ system with spark current I and a cable discharge system with a current I_c, respectively. Working gas: air at 1 atmosphere. Electrode gap: 0.7 mm.

But though temperature and volume of the spark plasma may be sufficiently high to effect pure thermal ignition according to the concept of minimal flame /1/, it can be deduced that this is not very likely in view of the results presented above. It can be concluded from rapid dissociation and high carrier density, that the major part of the supplied energy is still stored in the plasma particles as potential energy and that processes should be more probable therefore, making use of it.

We may conclude, that the transfer of the electrically supplied energy to the spark plasma can be followed by suitable experimental means and that a great deal of understanding has been gained already. Yet, more efforts are required to clear up the transfer of energy from the plasma to the combustion wave. It has been shown however that there are experimental and theoretical approaches for doing this in spite of the very short time intervals involved.

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New Spectroscopic Investigations of the Reaction Processes in Otto-Engines

Prof. Dr.-Ing. Hans May
Prof. Dr. rer. nat. Helmut Ehrhardt
Dipl.-Ing. Werner Müller

To perform spectroscopic measurements a single-cylinder test engine was developed. During the power stroke pressure and spectral radiation density at the band head of the OH-radical at 3064 Å and at the Na-line at 5891 Å were measured and registered. By means of these measured variables the course of temperature in the cylinder was calculated. The first results are shown and discussed.

Un moteur d'essai monocylindrique de type "Otto" a été développé pour l'éxécution de mesures spectroscopiques. Durant ces essais l'évolution de la pression et la densité spectrale de rayounement de la tête de bande du radical OH pour une longveur d'oude de 3064 Å et la ligne Na pour 5891 Å ont été mesurées et enregistrées. A l'aide de ces valeurs on a déduit l'évolution de la température dans le cylindre. On présente ici et on discute les premiers résultats des mesures.

Zur Durchführung spektroskopischer Messungen wurde ein Einzylinder-Otto-Versuchsmotor entwickelt. Während des Arbeitstaktes werden Druckverlauf und spektrale Strahldichte am Bandenkopf des OH-Radikals bei 3064 Å und an der Na-Linie bei 5891 Å gemessen und registriert. Mit Hilfe dieser Meßgrößen werden Aussagen über den Temperaturverlauf im Zylinder gemacht. Die ersten Meßergebnisse werden dargestellt und diskutiert.

1. Theoretical Basis for Determining the Emission-Absorption-Temperature

On account of the relative high temperature of combustion and the fast change of state of the gas mixture during the thermodynamical process of Otto-engines the direct measurement of the gas temperature is a problem which cannot be solved satisfactorily by the traditional measuring methods. So it is advantageous to utilize the temperature-dependence of the radiation of hot gases, to determine the temperature by means of spectroscopic measuring methods.

If it is possible to determine the emission and absorption of the gas transmitting this by the radiation of a reference source, it is obvious to select the emission-absorption-method. The physical basis of this procedure is the Kirchhoff's and Planck's law of radiation.

$$\frac{f_\lambda(T_g)}{k_\lambda(T_g)} = L_{\lambda,s}(T_g) \qquad \text{Kirchhoff's law} \qquad (1)$$

$$L_{\lambda,s}(T_g) = \frac{c_1}{\lambda^5}\cdot\left(e^{c_2/\lambda\cdot T_g}-1\right)^{-1} \qquad \text{Planck's law} \qquad (2)$$

$$c_1 = 2\,h\,c_0^2 = 1{,}191\cdot 10^{-12}\ \mathrm{Wcm}^2$$

$$c_2 = \frac{h\,c_0}{k} = 1{,}438\ \mathrm{cmK}$$

In Kirchhoff's law f_λ means the spectral emission-coefficient, which is defined as the radiated power emitted by the unit volume of the radiating gas per wave-length unit into spheradian unit. The spectral absorption-coefficient k_λ is defined as the radiation power which is absorbed from the gas per length-unit of the optical axis related to the spectral radiation density at the begin of the section. The ratio of these quantities is equal to the spectral radiation density of a "black body" at the gas temperature T_g, provided radiative and thermal equilibrium. Planck's law sets up the connection with the gas temperature.

The condition of radiative equilibrium on which Kirchhoff's law is based is only satisfied for the model of a closed cavity. Nevertheless an equilibrium can also be accepted for practical investigations if the gas radiation is only refered to a spontaneous emission which is dependent on the gas temperature. The second condition of thermal equilibrium makes it necessary to investigate wether the Boltzmann equation is satisfied for the gas and the measured spectral line or not.

$$f_{nm} = \frac{1}{4\pi} \cdot A_{nm} \cdot h \cdot \nu_{nm} \cdot N \cdot \frac{g_n \cdot e^{-E_n/k \cdot T}}{Z(T)} \qquad (3)$$

f_{nm} = line emission coefficient
A_{nm} = transition probability for emission
h = Planck's constant
ν_{nm} = frequency of the line
N = number of molecules or atoms per unit volume
g_n = statistical weight of state n
E_n = energy of state n
k = Boltzmann's constant
T = temperature
$Z(T)$ = partition function

Deviations from thermal equilibrium at combustion processes and rapid changes of state are possible.

The problem how thermal non-equilibrium influences the emission-absorption-temperature will be discussed in the following.

In praxis often will be found that the population of the different degrees of freedom like electronic exitation, vibration and rotation show a distribution which corresponds to the Boltzmann equation, however with different temperature-parameters (T_e, T_v, T_r) which are not equal to the gas temperature.

$$T_e \neq T_v \neq T_r \neq T_g \qquad (4)$$

The measured emission-absorption temperature in that case may be T^*. Then Kirchhoff's law can be written as follows:

$$\frac{f_\lambda(T^*)}{k_\lambda(T^*)} = L_{\lambda,s}(T^*) \qquad (5)$$

and in case of the thermal equilibrium

$$\frac{f_\lambda(T_g)}{k_\lambda(T_g)} = L_{\lambda,s}(T_g) \tag{6}$$

Hence it follows the equation

$$\frac{L_{\lambda,s}(T^*)}{L_{\lambda,s}(T_g)} = \frac{f_\lambda(T^*)}{f_\lambda(T_g)} \cdot \frac{k_\lambda(T_g)}{k_\lambda(T^*)} \tag{7}$$

This equation can be rearranged by the aid of Planck's law and the Boltzmann equation using the Born-Oppenheim approximation about the omission of the influence of the exitation of different degrees of freedom.

$$\frac{1}{T^*} - \frac{1}{T_g} = \frac{1}{\Delta E_{nm}}\left[\Delta E_e\left(\frac{1}{T_e} - \frac{1}{T_g}\right) + \Delta E_v\left(\frac{1}{T_v} - \frac{1}{T_g}\right) + \Delta E_r\left(\frac{1}{T_r} - \frac{1}{T_g}\right)\right] \tag{8}$$

In this ΔE_{nm} means the responsible energy gap due to the spectral line which will be measured, ΔE_e, ΔE_v and ΔE_r the parts of electronic, vibrational and rotational degree of freedom.

$$\Delta E_{nm} = \Delta E_e + \Delta E_v + \Delta E_r \tag{9}$$

T_e, T_v, T_r are the parameters substituting the gas temperature in the Boltzmann equation, in the case of non-equilibrium. For the most usual case, when the spectral line is caused by a transition including a change of electronic exitation the following can be said about the magnitude of the energy differences.

$$\Delta E_e >> E_v > E_r \tag{10}$$

In consideration of this fact in equation (8) follows:

$$T^* = T_e \tag{11}$$

Thus the measured emission-absorption-Temperature T^* is equal to the temperature-parameter for the electronic excitation T_e corresponding to the Boltzmann equation. Non-equilibrium of the degrees of freedom vibration and rotation do not influence the measured value. This statement is important in so far as non-equilibrium phenomena were indicated for rational and vibrational temperature in combustion processes [1].

So the measurement at a spectral line with electronic quantum transition in the visible and ultraviolet region of the spectrum is advantageous.

As the result of these considerations the supposition of thermal equilibrium, as condition for the validity of Kirchhoff's law, will be reduced to the supposition only of equilibrium of the electronic excitation. Wether this can be assumed or not has to be checked in each case.

To determine the temperature the ratio $f_\lambda(T_g)/k_\lambda(T_g)$ has to be ascertain by the aid of measurements.From the equation describing the radiation transport in gases

$$dL_\lambda = f_\lambda(x)dx - k_\lambda(x) \cdot L_\lambda(x) \cdot dx \tag{12}$$

it is possible to formulate by integration the spectral radiation density $L_\lambda(T_g)$, which is emitted from a gas layer with the thickness l, provided that the layer is isothermal and shows a homogenous distribution of the radiating molecules.

$$L_\lambda(T_g) = \frac{f_\lambda(T_g)}{k_\lambda(T_g)} \cdot \left[1 - e^{-k_\lambda(T_g)\cdot l}\right] \tag{13}$$

The term in parantheses on the right side of the equation (13) is the spectral absorbance α_λ.

Thus the ratio $f_\lambda(T_g)/k_\lambda(T_g)$ can be replaced by

$$\frac{f_\lambda(T_g)}{k_\lambda(T_g)} = \frac{L_\lambda(T_g)}{\alpha_\lambda(T_g)} \tag{14}$$

The spectral radiation density of the gas $L_\lambda(T_g)$ will be obtained by measurements in the middle of a spectral line using a grating-spectrograph of high resolving power and the result has to be calibrated with a radiation-standard.

The spectral absorbance α_λ will be calculated from the results of an additional measurement transmitting the gas layer by the radiation of a reference source.

$$\alpha_\lambda(T_g) = 1 - \frac{L_{\lambda,G+V} - L_{\lambda,G}}{L_{\lambda,V}} \tag{15}$$

In this equation $L_{\lambda,G+V}$ means the measured radiation density transmitting the gas layer by the radiation of a reference source, $L_{\lambda,G}$ is the radiation density of the gas layer and $L_{\lambda,V}$ that of the reference source. Using equation (14), Kirchhoff's and Planck's law the emission-absorption temperature can be calculated.

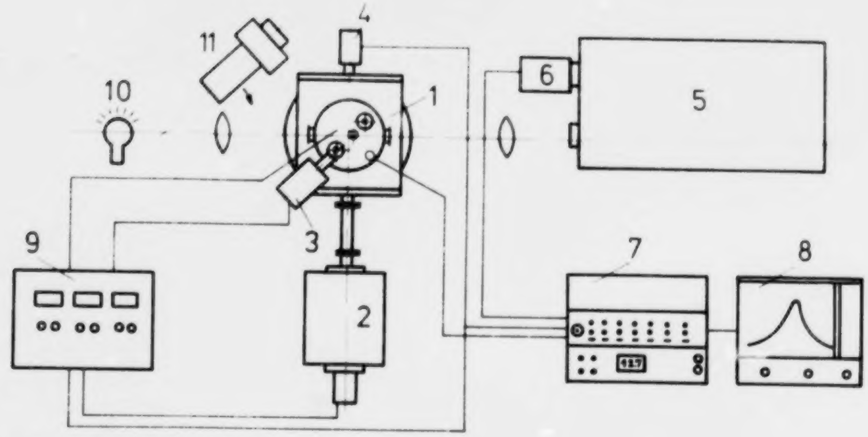
In practical applications of the described method it must be checked in each case whether the assumptions of isothermal gas layer and homogeneous distribution being the basis of equation (14) are fulfilled. In case of existing temperature profiles within the gas layer it can be shown by theoretical considerations and results of measurements that the measured temperature value is displaced in direction to the temperature maximum compared to the mass-mean temperature. Then the measured temperature can be taken as a measure indicating the maximum of the temperature profile.

The measurements discribed in the following were carried out at a test engine using a radiating gas component which occurs only in the burning zone but not in the unburned charge. Therefore the section, influencing the temperature results covers the actual zone of burned mixture which may be assumed as nearly isothermal.

2. Description of the Test Stand

In order to carry out spectroscopic investigations of the process of the Otto-engine a test engine was developed showing two quartz windows in the wall of the cylindric combustion chamber. The test engine is activated by an electromotor. A system of crankangle detector and electronic control unit permits the variation of several parameters, e. g. ignition point, begin of the data registration etc. The cylinder pressure is measured by use of a piezoelectric pressuremeter installed in the cylinder head. A grating spectrograph, specified in the following, is used for radiation measurement.

optical system:	Czerny - Turner
focal length:	1000 mm
grating:	1200 lines/mm
blaze wavelength:	3000 Å
reciprocal dispersion:	8 Å/mm
radiation detection:	photomultiplier



1 Test-Engine
2 Electro-Motor
3 Mixture-Preparation-Chamber
4 Crank-Angle-Detector
5 Grating-Spectrograph
6 Photomultiplier
7 Computer
8 Plotter
9 Control-Unit
10 Radiation-Source
11 Standard-Source

Fig. 1 Schematic Graph of the Test-Stand

The cylinder of the test engine is heated electrically and is charged with prepared fuel-air mixture before each test. Then the test engine is driven up to the desired speed by the electromotor and the charge is ignited at the desired ignition time. During the compression and expansion stroke, in which the combustion takes place, the variables mentioned above were measured in intervals of $1,5^{0}$ crank angle and stored in a computer.
In order to take cyclic variations into consideration the measurements of many testruns can be averaged automatically.
By use of the radiation values the emission-absorption temperatures and the spectral absorbance of the gas layer are calculated by the computer and figured by a plotter.
Additionally the mass-mean temperatures are calculated on the basis of the pressure measurements.

3. Results of Measurements

First results of measurements are given in Fig. 2.

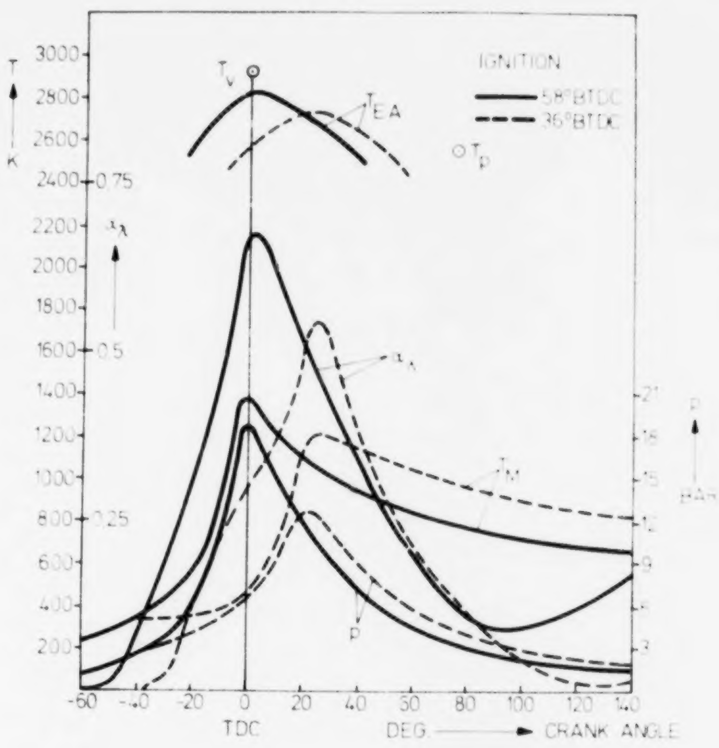


Fig 2 Comparison of E-A-Temperature, Mass-Mean-Temperature, Spectral Absorbance and Pressure for Two Different Ignition Points

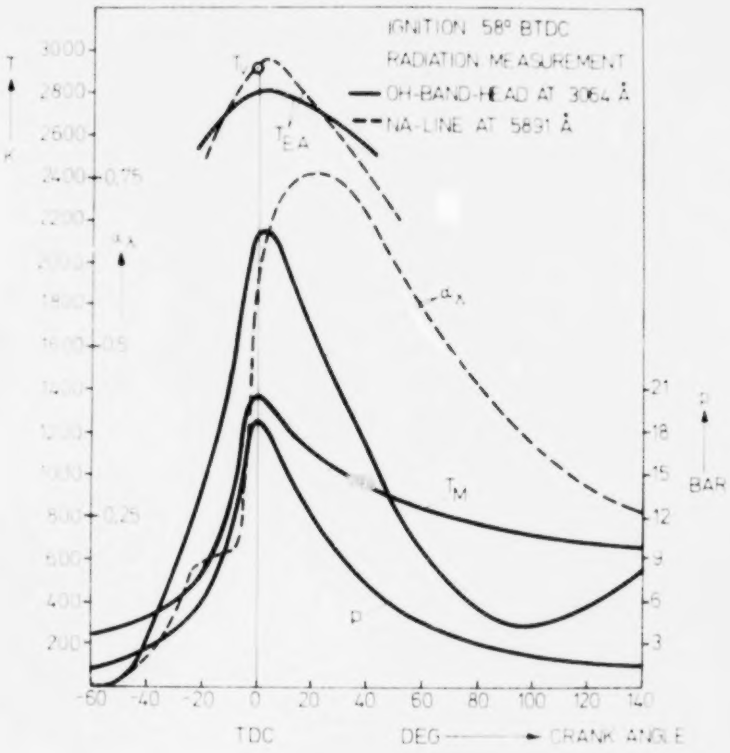


Fig 3 Comparison of E-A-Temperatures Obtained by Use of the Band-Head of OH at 3064 Å and the NA-Line at 5891 Å

The parameters of the test engine are the following:

speed $n = 1200$ rpm
equivalent ratio $\lambda = 1$
(actual air/stoichiometric air)
compression ratio $\varepsilon = 6.22$
charging efficiency $\lambda_L = 0{,}8$
temperature of air-fuel mixture $T_M = 380$ K
ignition point $\rho_i = 58^0$ respectively 36^0 BTDC

Additionally the temperatures calculated for the reference process of the Otto-engine assuming combustion at constant volume and chemical equilibrium T_v and for combustion at constant pressure T_p are marked. The emission-absorption temperatures are measured by use of the band head of OH at 3064 Å.
As can be expected the measured maximum temperatures lie between the calculated values for combustion at constant volume T_v and constant pressure T_p.
For the ignition point 58^0 BTDC the maximum temperature is closer to T_v because the combustion already starts during the compression stroke and is nearly finished at TDC.
For the ignition point 36^0 BTDC the major part of combustion takes place in the expansion stroke.
Because of the strongly increasing rate of combustion the maximum of temperature and pressure can be found at 25^0 ATDC. The maximum values are lower than these taken for earlier ignition caused by the beginning expansion. This case compared to the first one can be interpreted as increasing of the distance to the reference process for isochoric combustion respectively decreasing of the distance to the process with combustion at constant pressure.

The relative flat course of the measured temperature curves can be explained by the fact that OH-radicals only exist in the combustion zone. Therefore from the point of ignition till to the end of combustion the spectroscopic measurements are not affected by the temperature of the unburned mixture but only give information about the temperature of the burned and burning zone. This temperature value changes little with changing variables of state during the combustion process. At last during the expansion the spectral radiation of the gas decreases as rapidly with decreasing temperature

as its measurement becomes impossible.
The curve of the mass-mean temperature T_M is calculated on the basis of pressure measurements and shows values clearly below the emission-absorption temperatures essentially caused by the great temperature difference between unburned and burned gas. From this it can be concluded that with regard to the reaction mechanism, e. g. the NO-formation, the massmeantemperature is no useful value.

The curve showing the absorbance α_λ of the gas is a measure for the number of OH-radicals existing in the combustion zone. Beginning at the ignition point this number first increases rapidly due to the expanding zone of combustion. Finally when the flame front reachs at the windows the number of OH radicals is only dependent on the temperature of the gas layer decreasing during the expansion stroke.

Figure 3 shows two results of temperature measurements obtained by radiation measurements at the band head of OH at 3064 Å and at the Na-line at 5891 Å. The Na-line was produced mixing a trace of sodium into fuel, in the form of sodium-ethylate (C_2H_5ONa). It can be recognized that the Na-temperature first takes a course below the OH-temperature, then exceeds the OH-curve and finally again droops below the OH values. As can be expected excited Na-atoms already exist at lower temperatures as OH radicals will be formed. Therefore the region of spectroscopic measurement includes a part of unburned mixture near the burning zone. Therefore the resulting Na-temperature should be lower than the OH-temperature. The real course of the Na-temperature especially in the region where the curve exeeds the OH-temperature and the calculated value T_V also can be explained only by nonequilibrium excitation of Na during the combustion ptocess. This phenomenon will be investigated by further tests.
On the basis of the temperature measurements already carried out it can be concluded that the emission-absorption method represents a practicable way to measure combustion temperatures in the cylinder of internal combustion engines. Using the radiation of OH for temperature detection the measured value is not influenced by the unburned mixture and may be assumed as a basis for the classification of the reaction mechanism during the combustion and expansion

process e. g. with regard to the NO-formation.

Nomenclature

f_λ	Spectral emission-coefficient
k_λ	Spectral absorption-coefficient
$L_{\lambda,s}$	Spectral black body radiation density
L_λ	Spectral radiation density
α_λ	Spectral absorbance
λ	Wavelength of light
f_{nm}	Line-emission-coefficient
A_{nm}	Transition probability for emission
h	Planck's constant
ν	Frequency of light
N	Number of atoms or molecules per unit volume
g_n	Statistical weight of state n
E_n	Excitation energy of state n
k	Boltzmann's constant
$Z(T)$	Partition function
l	Thickness of gas layer
T_{EA}	Emission-absorption-temperature
T_v	Maximum temperature of the reference process of the Otto-engine (combustion at constant volume) calculated for chemical equlilibrium
T_p	Maximum temperature of the process assuming combustion at constant pressure calculated for chemical equlibrium

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Relations between obtainable mixture preparation, exhaust gas re-circulation, exhaust emissions, and fuel consumption of Otto cycle engines

G.R. HAERTEL Ing. (grad.)
Deutsche Vergaser GmbH & Co. KG
4040 Neuss, Leuschstrasse 1

For the conventional Otto cycle engine the combustion of very lean mixtures most likely represents the alternative to the exhaust afterburning to comply with the greatly reduced limits for exhaust emissions. It is the object of the research and development efforts to investigate the factors influencing the mixture formation and preparation, as well as the design parameters in simulating-, engine test bed- and vehicle tests. First individual results are given.

La combustion de mélanges très pauvres présente probablement pour le moteur traditionnel de carburation (moteur Otto) la solution alternative à la post-combustion des gaz d'échappement pour observer des limites fortement réduites des émissions de gaz d'échappement. Le projet d'étude et de développement a pour but l'étude des facteurs influençant la formation et la préparation du mélange et des paramètres de construction dans des essais de maquette, de banc moteur et de vehicule. Premiers résultats individuels seront indiqueés.

Die Verbrennung sehr magerer Gemische stellt für den herkömmlichen Ottomotor wahrscheinlich die Alternative zur Abgasnachverbrennung für die Erfüllung stark reduzierter Grenzwerte der Abgasemissionen dar. Das Forschungs- und Entwicklungsvorhaben bezweckt die Untersuchung von die Gemischbildung und - aufbereitung beeinflussenden Größen und konstruktiven Parametern in Modell-, Motorprüfstands- und Fahrzeugversuchen. Erste Einzelergebnisse werden genannt.

Relations between obtainable mixture preparation, exhaust gas re-circulation, exhaust emissions, and fuel consumption of Otto cycle engines

Introduction:

In spite of substantial progress in the development of novel "clean" prime movers for automotive vehicles the conventional Otto cycle engine is expected to remain the predominant power unit for the passenger car after the year 1980. The more stringent emission control legislation for Otto cycle engines decided or scheduled by the legislator for that period either require the general introduction of a thermic or catalytic post combustion system or the consequent exploitation of still existing development reserves to influence the combustion within the Otto cycle engine. Although the thermic and catalytic afterburning of the exhaust gases has just been introduced on a large scale in the USA and the systems will perhaps prove their technical maturity in the near future, owing to principal consideration it will be a particular challenge for the engineer to achieve the targets by means of the more economic approach - the combustion of extremely lean mixtures in the Otto cycle engine. In addition to the efforts aimed at the same targets already sponsored by the same sponsor this research and development program has the following objects:

1. Simulating investigations on the preparation of the intake mixture.
1.1. Investigation of the influence of boundary conditions.
1.2. Influence of design parameters on various carburetter models and spraying nozzles.

2. Determination of lean running limits in engine tests.
2.1. Comparison of various devices for mixture formation (fully warmed up engine, stationary operation).
2.2. Comparison of various devices for mixture preparation (fully warmed up engine, stationary operation).
2.3. Investigation of selected combinations of devices for mixture formation and preparation.
2.3.1. With fully warmed up engine, stationary operation, also using model fuels with high boiling range.

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2.3.2. With not fully warmed up engine, instationary operation -

3. Driveability tests and emissions in various emission tests.

3.1. Calibration of selected combinations of devices for mixture formation and preparation to comply with the following requirements with fully warmed up engine: good driveability, favourable fuel consumption, low exhaust emissions.

3.2. Adaptation of the calibration of selected combinations according to 3.1. to the requirements of the not fully warmed up engine.

4. Control devices for external exhaust gas recirculation.

4.1. Determination of various control factors on the engine test bed, stationary operation.

4.2. Development of control devices for selected control factors on a special test stand.

4.3. Evaluation of the control devices for stationary operation on the engine and instationary operation in the vehicle.

Within the time covered by this report the test installations and devices for the simulating investigations for the preparation of the intake mixture, and for the engine test to determine the lean running limits were built and the tests initiated.

To 1: Simulating investigations for the preparation of the intake mixture

Investigations of the influence of boundary conditions.

Precipitations of the fuel occurring in the intake manifold when the mixture is incompletely prepared render the distribution difficult and lower the transport speed of the fuel. A measurement of the quantity of these precipitations under conditions coming close to actual practice can result in recognitions concerning the preparation of fuel. Here in a first approximation the quantity of fuel precipitated on the intake manifold walls may be considered,as degree of precipitation set into relation to the quantity admitted,as a measure for the quality of the preparation. The more fuel is found on the wall after the flow has been rerouted once or twice the worse is the preparation of the mixture.

Test installation and execution of test.

The test installation is shown schematically in figure 1. The main part is an intake manifold of a 4-cylinder inline engine of which only one branch for two cylinders is used. In the hot spot bottom and at the outlet of the manifold precipitated fuel can be drained-off separately in order to measure the quantities. For all tests the intake air is taken from a climatized room with a temperature of 293 K and a relative humidity of approximately 40%. The admitted fuel also has a temperature of 293 K.

From engine tests with a similar intake manifold the following values for the air flow and the manifold pressure in the simulating test were deducted:

air flow $\dot{m}_L$ in kg/h	30	42,5	50	57,5	67,5	80
intake manifold pressure p_H in mbar	613	627	910	997	833	988

Till today, beside other tests with a spraying nozzle as device for mixture preparation, for the above combinations of air flow and manifold pressure with the same fuel the air ratio and with constant air ratio the fuel properties were varied.

The fuel data are:

boiling range	60/95	100/140	145/200
density at 293 K in g/cm^3	0,69	0,74	0,78
kinematic viscosity at 293 K in mm^2/s	0,55	0,75	1,25
thermal capacity in J/(g.K)	2,22	2,22	1,97
mean molecular mass	92	112	140

The figures given for the boiling range denominate the begin and the end of the boiling in centigrade. For the air ratio 1 a mixture ratio of 14,9 kg air/kg fuel is assumed.

Some test results

The results of the current test program permit a survey on the influence of the fuel characteristics as well as of the air ratio.

With increasing air ratio the proportion of the fuel found on the wall at the manifold outlet - the degree of precipitation - is greatly reduced, fig. 2. With high absolute pressures in the manifold with air ratios of 1o and more there is no more liquid fuel at the intake manifold outlet. With low pressures in the manifold there is no further fuel precipitation already with air ratios of approximately 3.

Fig. 3 shows a strong dependency of the degree of precipitation from the fuel characteristics. Pro rata of the low boiling fuel a smaller proportion is precipitated than from the medium boiling fuel while the fuel with the high boiling range will be found almost completely on the wall before the manifold outlet. A strong dependency from the intake manifold pressure is apparent while a direct dependency of the degree of precipitation from the air flow cannot be seen.

To 2: Determination of the lean running limits for stationary engine operation

Comparison of various devices for mixture formation

If the intake mixture of an engine in stationary operation is leaned out, we may expect that with a homogeneous mixture high air ratios may be obtained. Conversely we may presuppose that with a less uniformly prepared intake mixture the lean limits will be reached at smaller air ratios owing to the increasing cyclic fluctuations of the pressure development in the cylinder. The lean limit may, therefore, be used as criterion for the quality of the preparation of the intake mixture when various devices for mixture formation and mixture preparation are used. As the lean limit of an engine is also dependent from a number of other parameters, these have to be kept as constant as possible during these test series. In addition to the ignition system, the valve timing, the temperature level of the engine and the intake air this also applies to the mixture distribution. The mixture distribution is primarily dependent on the design of the channels through which the mixture is conducted and has to be brought to comparable values for each system to be tested by which mixture is formed and prepared.

Test installation and execution of test

Fig. 4 shows schematically the test installation on the engine test bed and the measuring devices. For certain combinations of devices for mixture formation and preparation the lean limits are determined with variable ignition points for six points on the engine characteristics. The limit is defined by a steep rise of unburnt hydrocarbons in the exhaust gases or by noticeable fluctuations of the torque. The measuring points are distributed on the engine characteristic curves to cover the load, rpm, and power range of urban traffic which is of particular interest.

Measuring points within the engine characteristics:

engine rpm in min^{-1}	1000	1000	2000	2000	3000	3000
torque in Nm	28	84	28	84	28	84
engine output in kW	2,9	8,8	5,9	17,7	8,8	26,5

Results

The lean running limits were already determined for the following combinations:

1) Compound carburetter 32/32 DIDTA standard	standard manifold with hot spot
2) Single barrel carburetter 35 PDSIT	standard manifold with hot spot
3) Compound carburetter 2A1 with constant pressure stage	standard manifold with hot spot
4) Constant depression carburetter 175 CDET	standard manifold with hot spot

Fig. 5 shows typical results to 1) for one operating point. The individual results obtained till today cannot be represented in the above form owing to lack of space. A summary only appears to be reasonable after conclusion of the measuring series "Lean running limits in stationary operation" as only then a comparative evaluation may be made.

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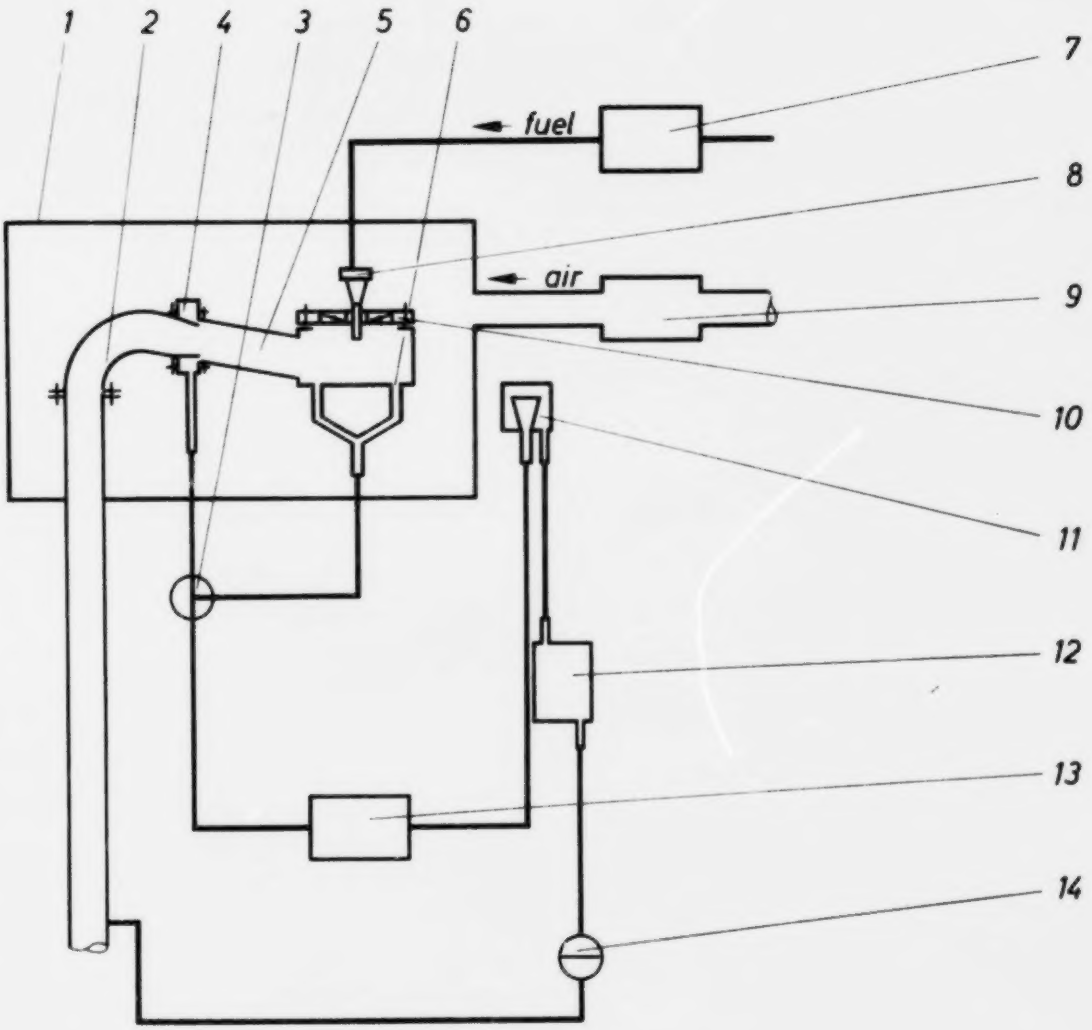


Fig. 1 Schematical diagram of the measuring device for the fuel precipitation

1 flow bench test chamber, 2 intake manifold to vacuum pump, 3 three-way-valve, 4 separator at manifold outlet, 5 modified intake manifold of a 4-cylinder-engine, 6 separator, hot spot, 7 flow meter, inlet quantity, 8 injection nozzle, 9 air volumeter, lo dual throttle body, 11 overflow, 12 reservoir, 13 flow-meter, quantity precipitated, 14 shut-off valve

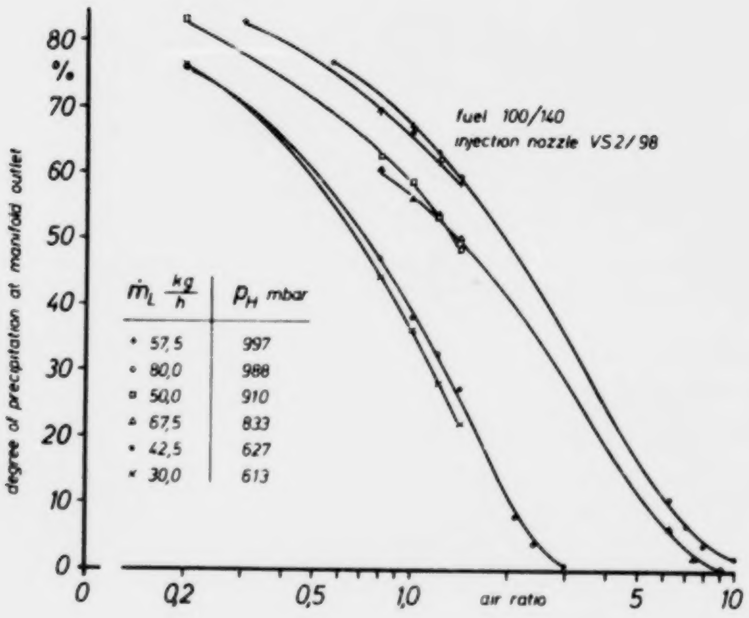


Fig. 2 Influence of air ratio on the degree of precipitation

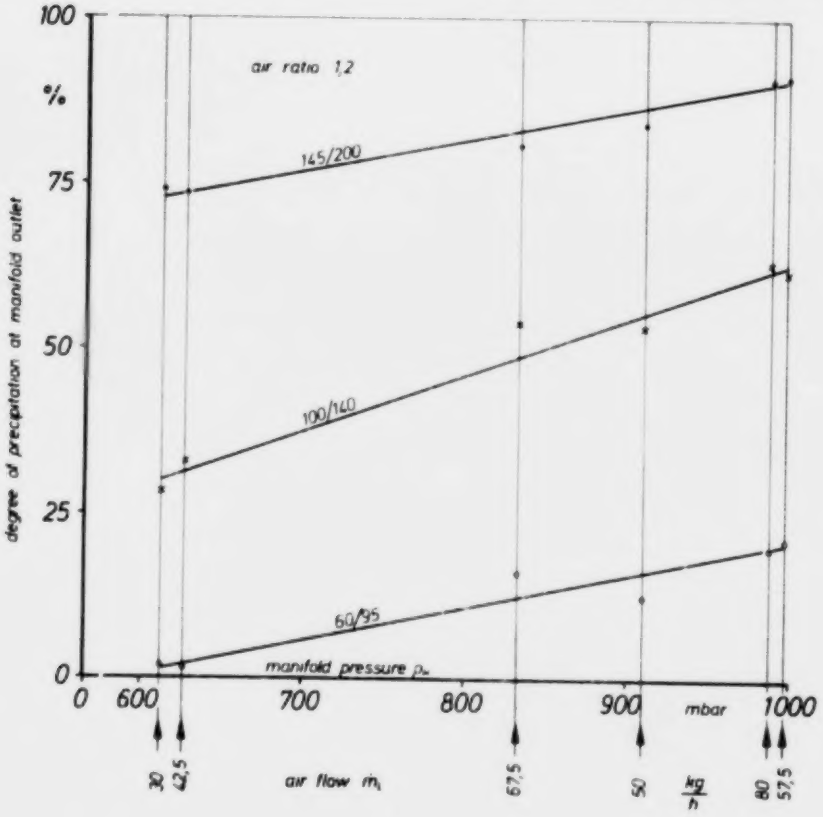


Fig. 3 Influence of the fuel on the degree of precipitation

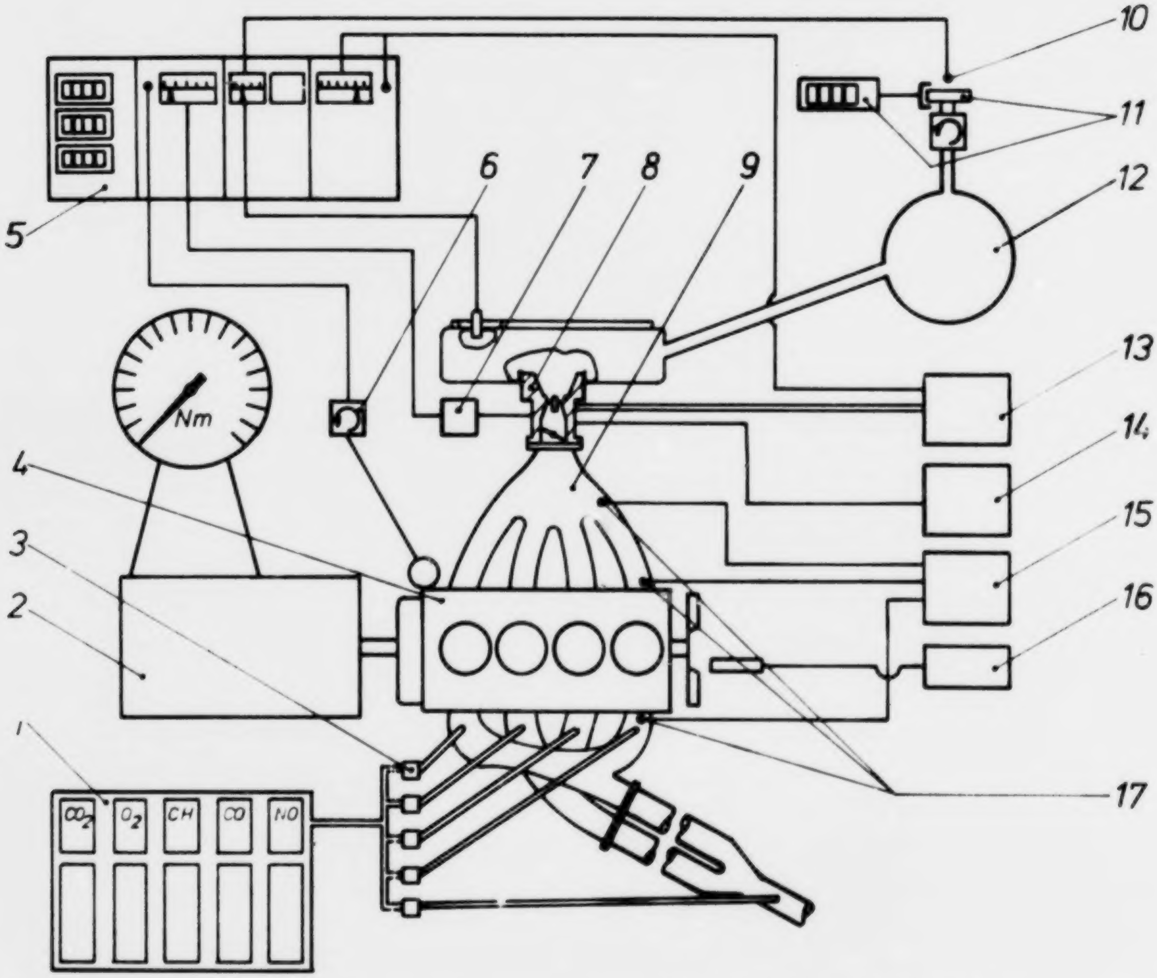


Fig. 4 Test installation on the engine test bed with measuring devices, schematical diagram

1 exhaust gas analyser system: IR analysers for CO, CO_2, C_6H_{14}, NO, 2 engine power dynamometer, 3 magnetic valve, 4 engine: water-cooled 4-cylinder, 4-stroke-engine, engine capacity 1,9 l, compression ratio 8,6 : 1, 5 control table with indicators for engine rpm, ignition timing, measuring time, temperatures, 6 device for ignition timing, 7 remote control indication for throttle butterfly position, 8 device for mixture formation, 9 device for mixture preparation, 1o remote thermometer. 11 rotary piston gas meter with remote digital indication, 12 surge tank, 13 adjusting device for the air ratio, 14 fuel flow meter with digital indication, 15 twelve point printer, 16 instrument for measuring ignition and rpm with digital indication, 17 measuring points for temperature on the intake manifold and the exhaust manifold.

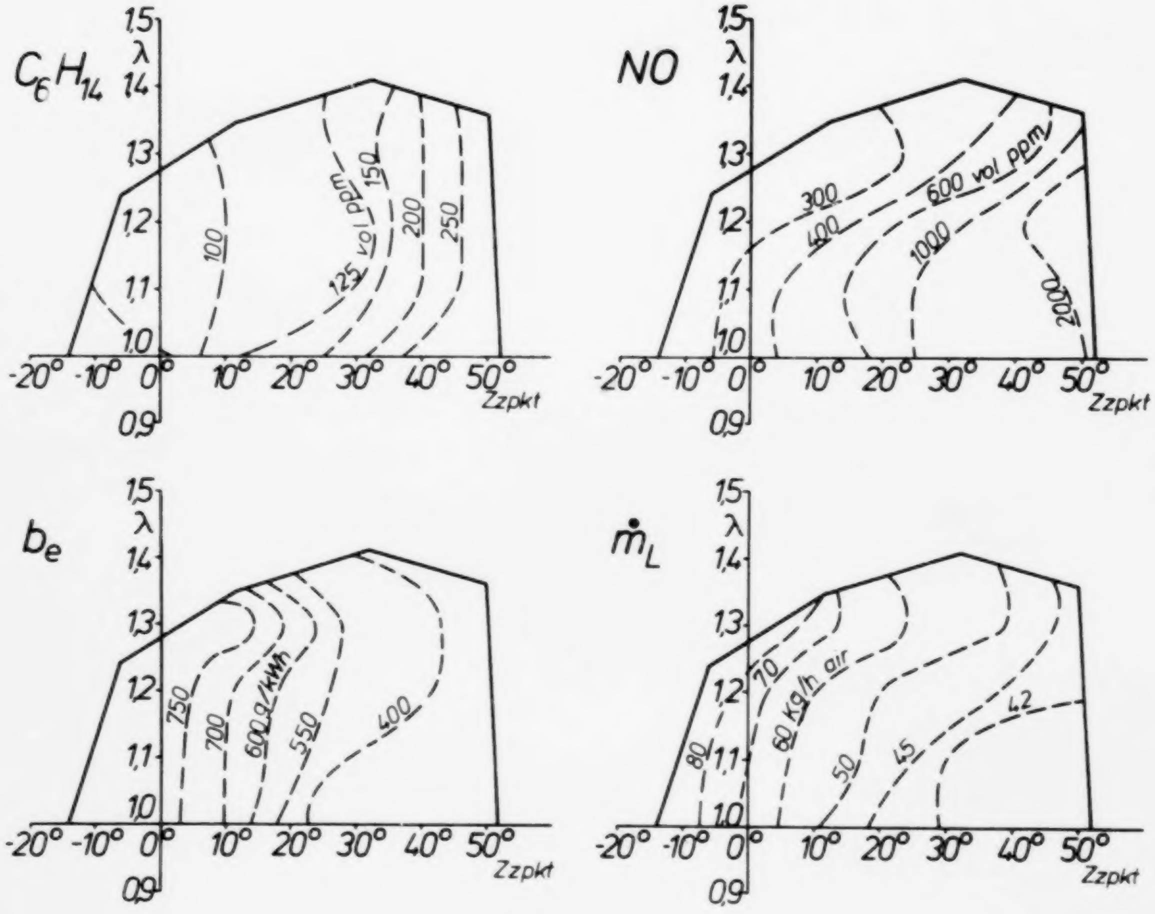


Fig. 5: λ/Zzpkt-family of curves for the concentration of unburnt hydrocarbons as C_6H_{14}, nitric oxide NO, specific fuel consumption b_e and air flow m_L with running limits for the point 2000 min^{-1}, 28 Nm, 5,9 kW for a series carburetter and a series intake manifold

$$\lambda = \text{air ratio} = \frac{\text{actual air fuel ratio}}{\text{stoichiometric air fuel ratio}}$$

Zzpkt = ignition point in degree crankshaft angle before top dead center.

Emissionsarmer Fahrzeugmotor auf der Basis des AD - Vielstoffverfahrens.

G. FINSTERWALDER , H. KÜPPER

KLÖCKNER-HUMBOLDT-DEUTZ AG, KÖLN

The aim of the research project is an automotive engine having the power-to-volume ratio of the Otto engine and the economy of the Diesel engine, while fulfilling the exhaust-gas regulations without after-treatment of the exhaust gases. The AD-Multifuel process,(a direct injection process with applied ignition derived from Diesel engine) serving as a basis for the project has been investigated with regard to its supercharging possibilities. No incipient knocking could be detected within the operating range examined.

Les récherches entreprises ont pour but de déveloper un moteur de vehicle fournissant la puissance volumique du moteur Otto et offrant le rentabilité du moteur Diesel, les préscriptions relatives aux gaz d' échappement étant respectés sans traite - ment supplémentaire. Le procédé polycarburant AD, (procédé d' injection directe avec allumage indépendente dérivé du moteur Diesel) qui est à la base des recherches a fait l' objet d' examens en vue des possibilités de suralimentation offertes. Une limite de cognement n' a pu être constaté dans la plage de service examinée.

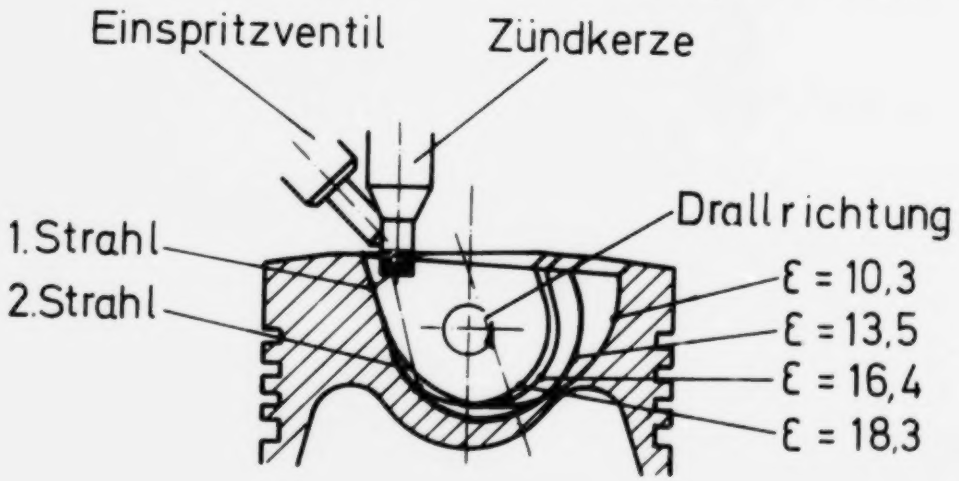
Ziel des Forschungsvorhabens ist ein Fahrzeugmotor mit der Leistungsdichte des Ottomotors und der Wirtschaftlichkeit des Dieselmotors bei Einhaltung der Abgasvorschriften ohne Abgas - nachbehandlung. Das dem Vorhaben zugrunde liegende AD - Viel - stoffverfahren (ein vom Dieselmotor abgeleitetes Direktein - spritzverfahren mit Fremdzündung) wurde auf seine Aufladbarkeit hin untersucht. Es konnte im untersuchten Betriebsbereich keine Klopfgrenze festgestellt werden.

Ziel des Vorhabens ist die Erstellung eines Fahrzeugmotors, der die Leistungsdichte des Ottomotors mit der Wirtschaftlichkeit des Dieselmotors verbindet und die Abgasvorschriften ohne Abgasnachbehandlung einhält. Da das dem Vorhaben zugrunde liegende AD - Vielstoffverfahren (1) vom Dieselmotor abgeleitet wurde und dessen guten Kraftstoffverbrauch hat, wurde zunächst der Schwerpunkt der Bemühungen auf die Anhebung der Leistungsdichte gelegt.

Die Leistung kann u.a. durch Erhöhen von Drehzahl, Luftausnutzung und Mitteldruck gesteigert werden. Im ersten Versuchsjahr wurde die Mitteldrucksteigerung durch Aufladung untersucht. Die Versuche wurden an einem 1-Zylinder-Motor mit 130 mm Hub und 125 mm Bohrung und einer Nenndrehzahl von $n_M = 2650\ \mathrm{min}^{-1}$ gefahren. Die Aufladung wurde mittels Preßluft aus dem Netz simuliert, der Abgasgegendruck mit einer Drosselklappe eingestellt. Die Ladelufttemperatur wurde durch eine elektrische Heizung variiert.

Als erstes wurden Verdichtungsverhältnis ε und Einlaßdrall $\frac{V_u}{V_a}$ im Hinblick auf größtmögliche Aufladbarkeit verändert. Dabei wurde von der Lage der Einspritzdüse und Zündkerze des AD - Verfahrens ausgegangen und die Brennraumform, wie im Bild unten dargestellt, abgewandelt.

Brennraumformen; Kerzen- u. Einspritzventillage



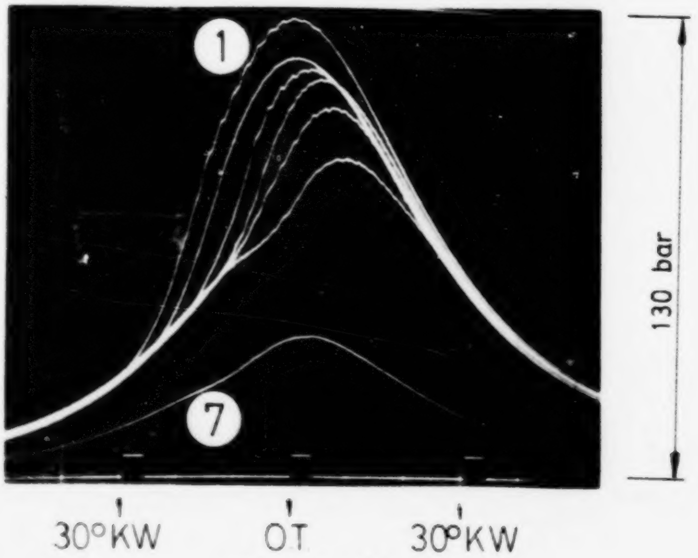
Das Ergebnis der ε - Variation geht aus dem Bild auf Seite 4 hervor. Die Versuche wurden durch entsprechende Aufladung mit konstantem Spitzendruck von p_{max} = 1oo bar für alle Verdichtungsverhältnisse und einer konstanten Ladelufttemperatur t_L = 6o° C gefahren. Als Kompromiss zwischen dem Wunsch nach größtmöglicher Aufladbarkeit und der Forderung nach befriedigendem Start- und Teillastverhalten, wurde ein Verdichtungsverhältnis von ε = 13,5 gewählt.

Der Einfluss des Verdichtungsverhältnisses auf den Brennraumdruckverlauf geht aus dem Bild auf Seite 5 hervor. Die Aufnahmen wurden mit einer Sekunde Belichtungszeit gemacht, was bei n_M = 16oo min^{-1} ca. 14 Durchläufen und bei n_M = 265o min^{-1} ca. 22 Durchläufen entspricht. Die Aufnahmen zeigen, unabhängig vom Verdichtungsverhältnis einen sanften, aussetzerfreien Druckverlauf ohne irgendwelche Klopferscheinungen. Die für die Aufladbarkeit wichtige Klopfgrenze wurde selbst bei Spitzendrücken von p_{max} = 13o bar nicht erreicht, wie aus untenstehendem Bild deutlich hervorgeht.

Einfluß des Einspritz-u.Zündbeginns auf den Verbrennungsdruckverlauf

Bohrung 125mm, Hub 130mm, ε 13,5
Hubvolumen 1595cm³, Einlaßdrall 2,5
Ladelufttemp. 60°C, Kraftstoff Norm.Benzin

(1) Einspritz-u. Zündbeginn (°KWvOT) = 50°
(2) " = 40°
(3) " = 30°
(4) " = 25°
(5) " = 20°
(6) " = 15°
(7) " = 20°

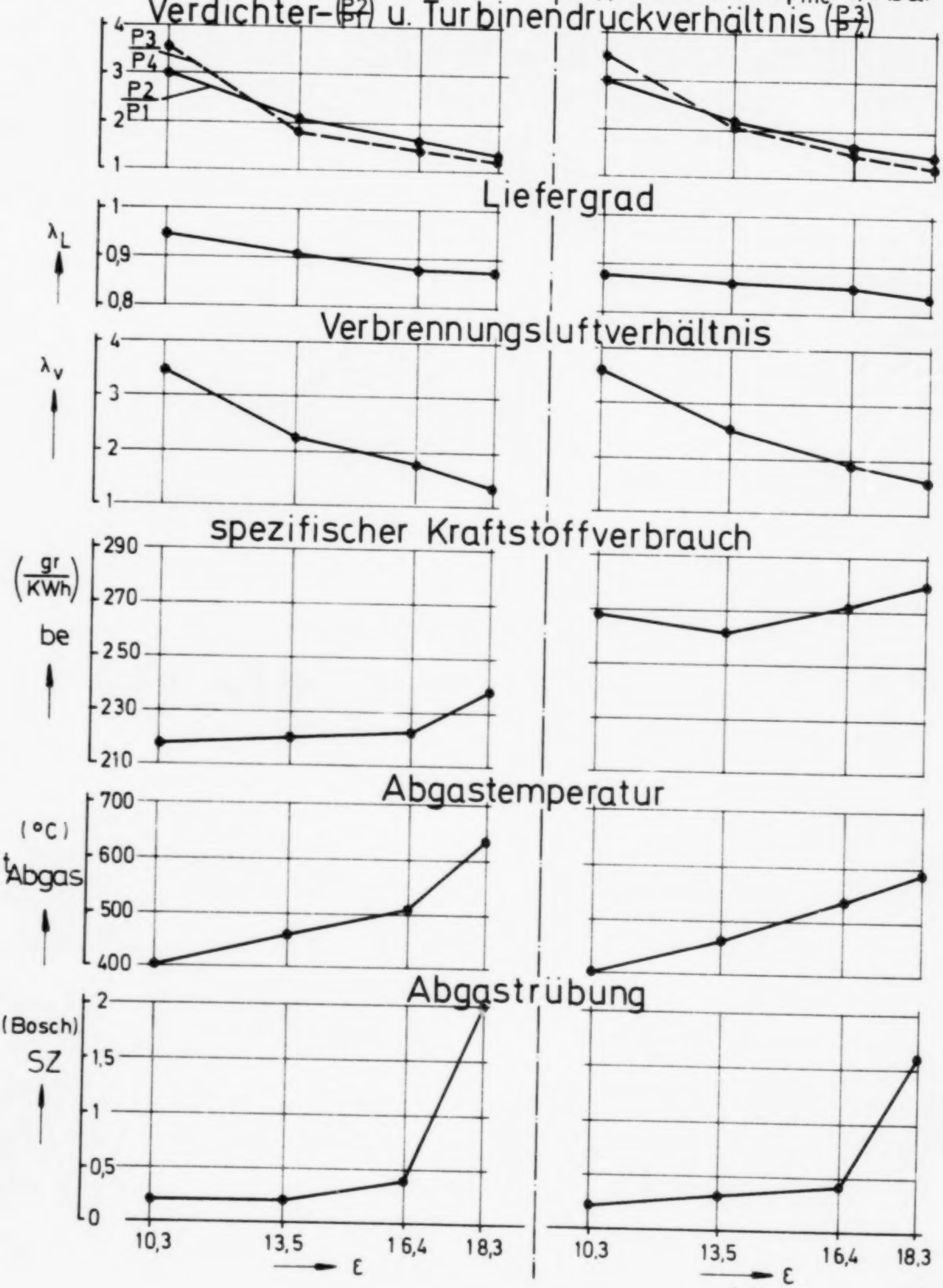


(1) bis (6) $n_M = 1600 min^{-1}$; p_{me} = 10 bar; $\frac{p2}{p1} = 2{,}1$; $\frac{p3}{p4} = 1{,}95$;
(7) $n_M = 1600 min^{-1}$; p_{me} = 1 bar; $\frac{p2}{p1} = 1$; $\frac{p3}{p4} = 1$;

Einfluß des Verdichtungsverhältnisses (ε)

Bohrung : 125mm ; Hub : 130mm ; Hubvolumen : 1595cm^3; Einlaßdrall : 2,5; Ladelufttemp : 60°C; Verbrennungsspitzendruck : 100 bar; Kraftstoff : Normalbenzin.

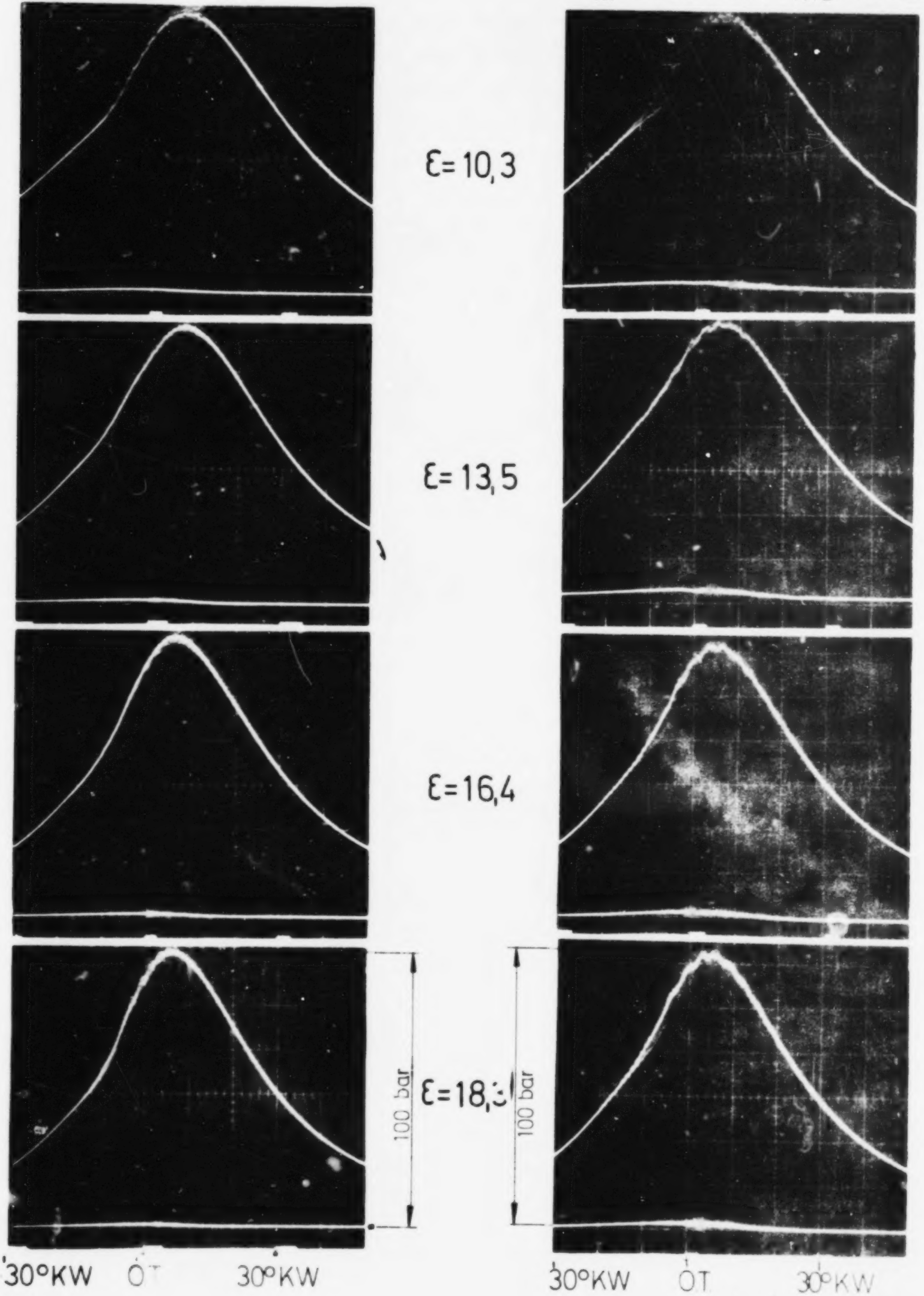
n_M: 1600min^{-1}; p_{me}: 10 bar | n_M: 2650 min^{-1}; p_{me}: 7,5 bar



Einfluß des Verdichtungsverhältnisses (ε)

$n_M = 1600\,\text{min}^{-1}$; $P_{me} = 10$ bar

$n_M = 2650\,\text{min}^{-1}$, $P_{me} = 7{,}5$ bar



Mit dem zugrunde liegenden Verdichtungsverhältnis von $\varepsilon = 13{,}5$ wurde im nächsten Schritt der Einlaßdrall variiert, siehe Bild auf Seite 7. Da mit steigendem Drall der Liefergrad sinkt, ist der kleinstmögliche Drall anzustreben. Seine untere Grenze wird durch Kraftstoffverbrauch und Abgastrübung bestimmt.

Hier wurde $\frac{V_u}{V_a} = 2{,}5$ gewählt.

Mit $\varepsilon = 13{,}5$ und $\frac{V_u}{V_a} = 2{,}5$ wurden anschließend die Teillastkurven des Bildes von Seite 8 gefahren. Die Oszillogramme im oberen Bildteil zeigen den Verbrennungsdruckverlauf der Volllastpunkte beider Drehzahlen.

Nachdem die Aufladbarkeit des AD-Verfahrens hinreichend gesichert ist, konzentrieren sich die laufenden Untersuchungen auf die Drehzahlfreudigkeit des Verfahrens.

Einfluß des Einlaßdralls $\left(\frac{V_u}{V_a}\right)$

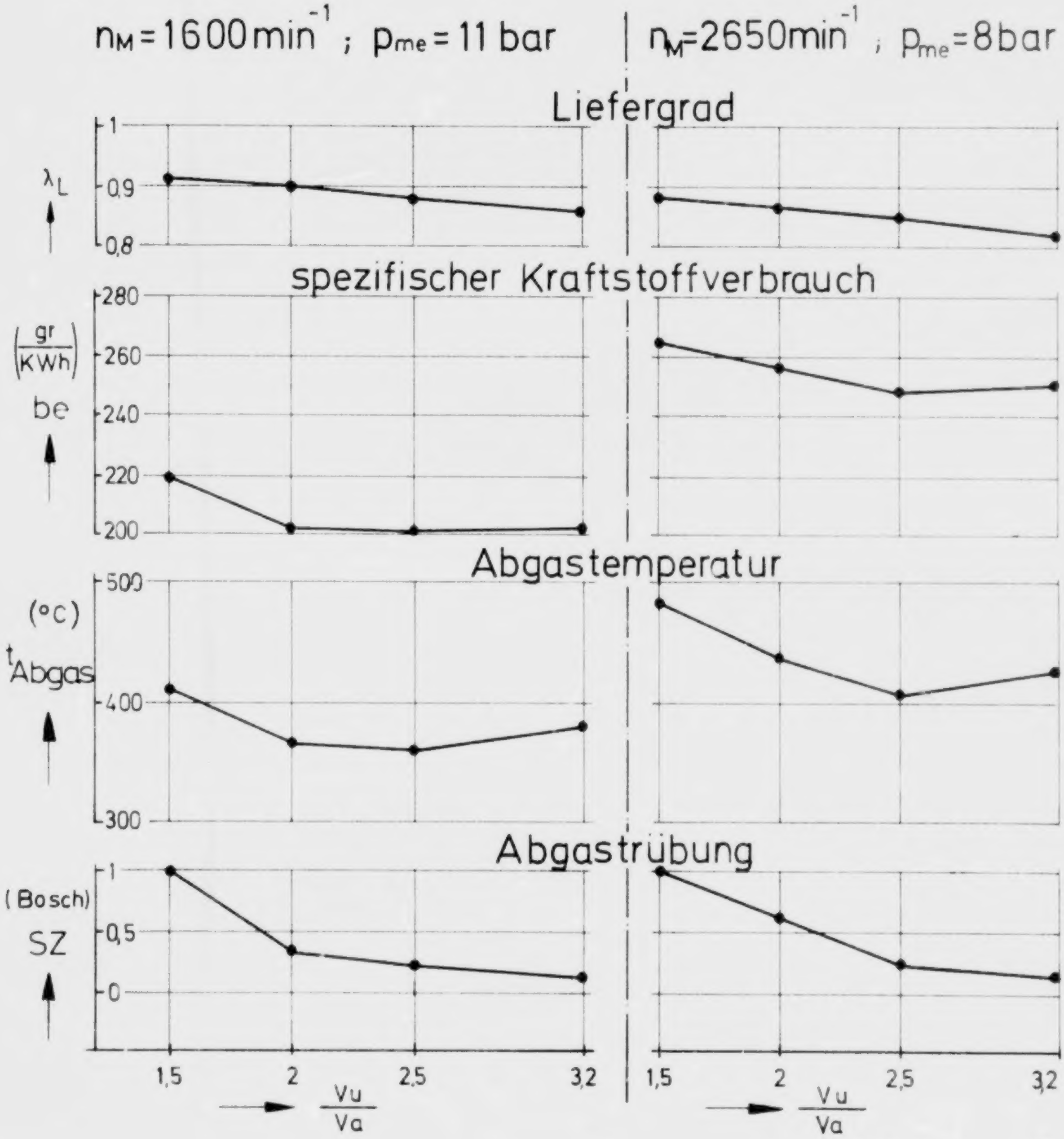
Bohrung: 125mm ; Hub: 130mm;

Hubvolumen: 1595 cm^3 ; ε: 13,5 ;

Ladelufttemperatur: 30° C ;

Verdichterdruckverhältnis $\left(\frac{p_2}{p_1}\right)$: 2 ;

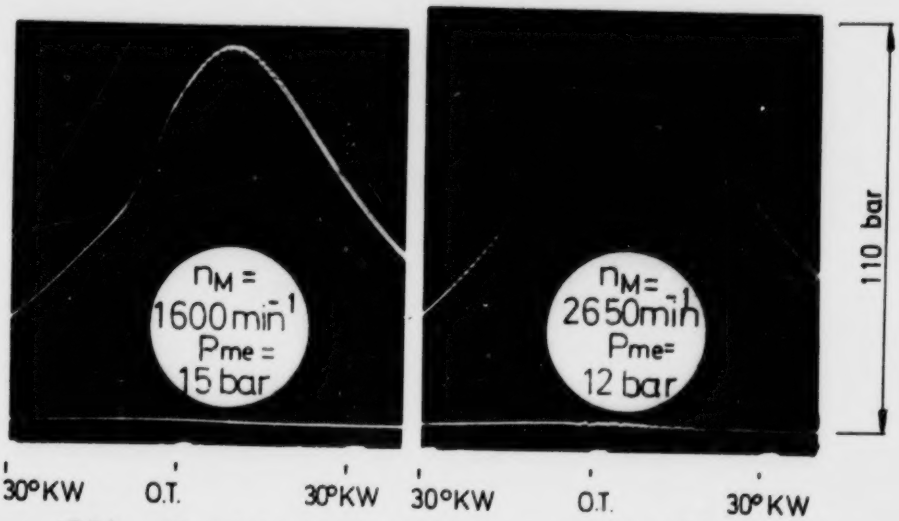
Turbinendruckverhältnis $\left(\frac{p_3}{p_4}\right)$: 1 ; Kraftstoff: Norm.Benzin

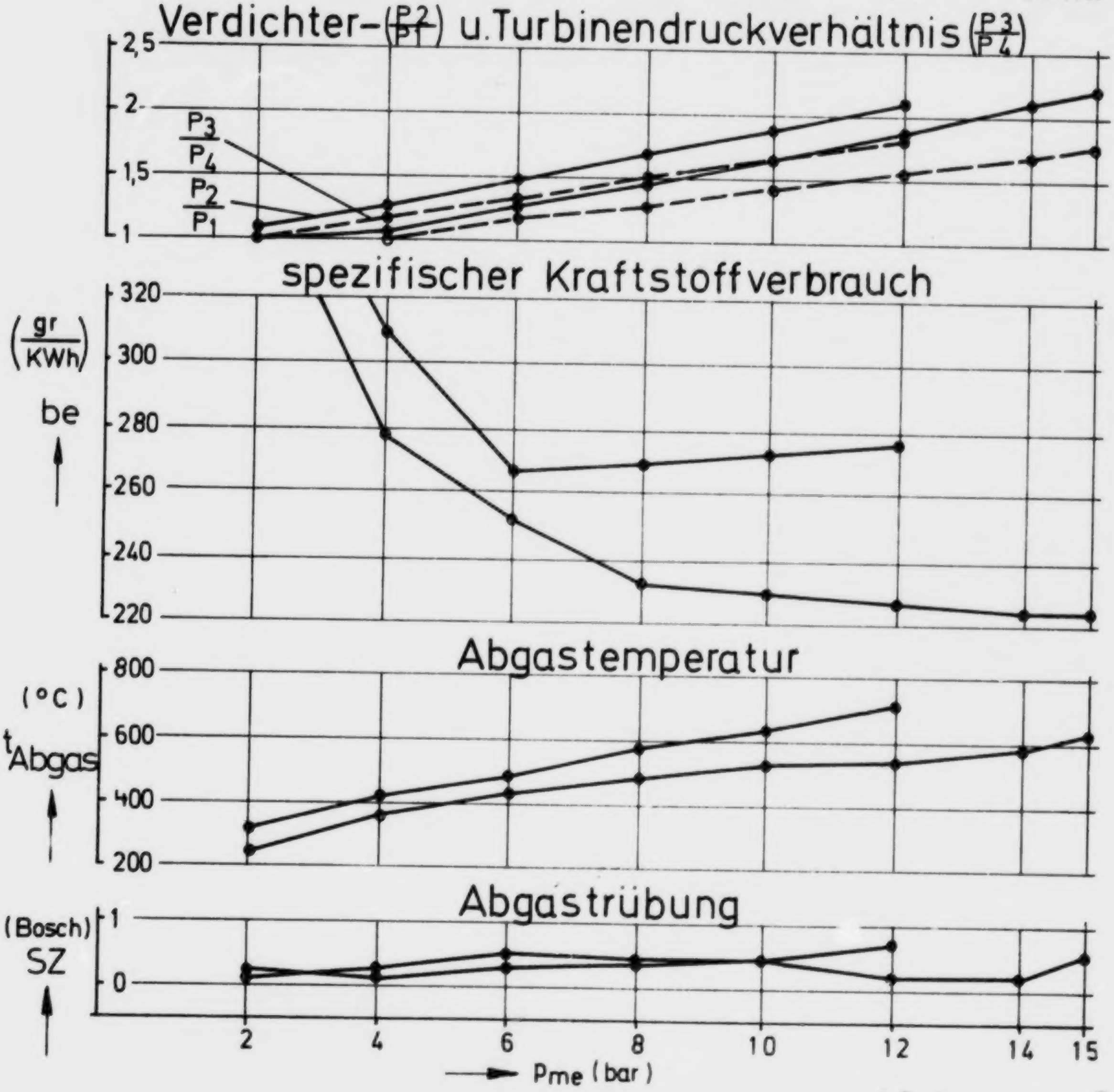


Pme-Kurven für optimiertes ε und optimierten Einlaßdrall

bei n_M = 1600 min^{-1} ○
und
n_M = 2650 min^{-1} ●

Bohrung : 125 mm
Hub : 130 mm
Hubvolumen : 1595 cm^3
ε : 13,5
Einlaßdrall : 2,5
Ladelufttemperatur : 60°C
Kraftstoff : Norm.Benzin





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(1) A New Deutz Multifuel System (SAE Paper Nr. 72o 1o3)
v. G. Finsterwalder

SINGLE CYLINDER TESTS CONCERNING A LOW EMISSION ENGINE BASED ON AD - MULTIFUEL PROCESS

Professor Dr.-Ing. F. PISCHINGER
Dipl.-Ing. G. SCHMIDT
Lehrstuhl für Angewandte Thermodynamik, RWTH Aachen

A single cylinder engine study was performed employing the AD-multifuel process of the Klöckner-Humboldt-Deutz AG. The engine was used in its original version. The possibility to improve emissions by simple modifications was investigated. Till now it was found that with regular gasoline it is possible to influence exhaust emissions and brake specific fuel consumption by variation of injection and ignition timing. Improvement in emissions without too much increasing in brake specific fuel consumption seems possible.

Ausgehend vom AD-Verfahren der Klöckner-Humboldt-Deutz AG wurden Untersuchungen an einem Einzylinder-Versuchsmotor durchgeführt. Die Versuche hatten eine Verbesserung der Abgasemissionen durch Variation einfacher Betriebsparameter zum Ziel. Die Ergebnisse der Abstimmungsversuche zeigen, daß sich durch Variation der Betriebsparameter Förderbeginn und Zündzeitpunkt die Emissionen verbessern lassen, ohne dabei eine zu starke Verbrauchsverschlechterung in Kauf nehmen zu müssen.

Investigations are based on AD-process from Klöckner-Humboldt-Deutz AG, well known from literature. The aim of this study is to reach the optimal results of brake specific fuel consumption and exhaust emissions, when this process is used with regular gasoline only. In the first stage of investigations reported here, this should be achieved by variation of simple engine parameters.

A single cylinder test engine was used in its original AD-version without any modifications. The fuel used was commercial regular gasoline. During the tests, timing of injection and ignition were varied independently over the whole speed range. For the beginning the tests were run at part load to avoid the danger of reaching too high engine temperatures.

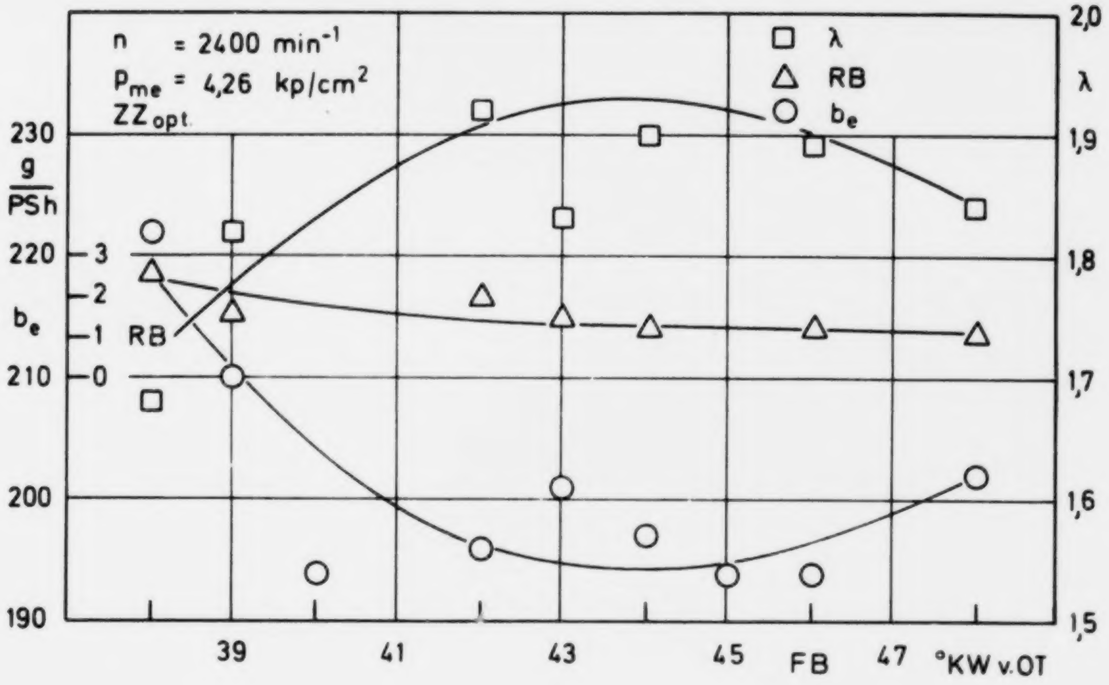

Fig. 1: Brake specific fuel consumption, soot emission (Bosch) and relative air-fuel ratio versus injection timing (start of pump delivery) before top dead center.

Figure 1 shows as result of the tests the brake specific fuel consumption, soot emission (Bosch) and relative air-fuel ratio versus injection timing for 2400 rpm and fixed bmep (bmep = 4,24 kp/cm^2). Ignition timing was adjusted for lowest brake specific fuel consumption.

Relative air-fuel ratio λ , which is also shown in this picture is inversely proportional to brake specific fuel consumption because no intake throttling was employed. The picture shows that brake specific fuel consumption clearly depends on injection timing and reaches optimum timing at 44 degrees crank angle before top dead center. Compared with the values for optimum adjustment for brake specific fuel consumption, NO emission can be improved remarkably when shifting injection timing towards top dead center, while hydrocarbons increase only slightly when doing so.

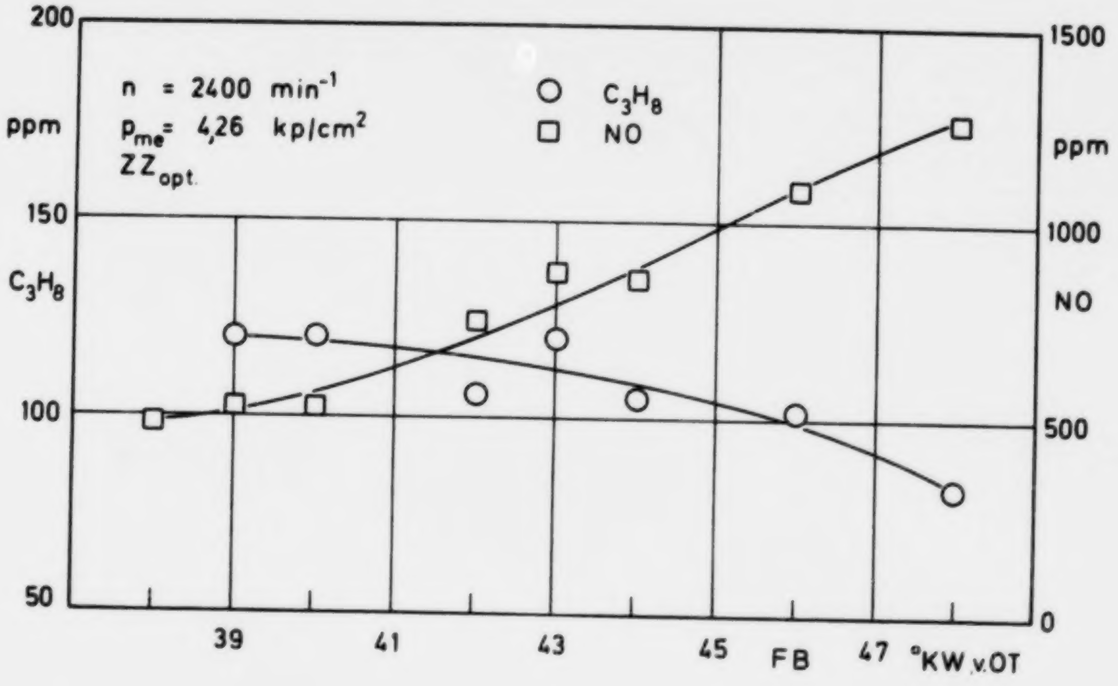

Fig. 2: Hydrocarbon- and nitric oxide emissions versus injection timing (start of pump delivery) before top dead center.

It is possible to find an acceptable compromise when shifting injection timing two or three degrees from point of optimum bsfc towards top dead center.

In order to sum up it can be stated that by variation of injection- and ignition timing only it is possible to influence NO emissions favourably without increasing brake specific fuel consumption too much. Further combustion parameters will be investigated in the future.

Studies for Improved Emission Control in Gasoline-Operated Automotive Engines by the Use of MAN's "FM" Combustion System

Dipl.-Ing. Wolfram Thielicke
Maschinenfabrik Augsburg-Nürnberg Aktiengesellschaft
85 Nürnberg
Katzwangerstraße 101

The targets of this research projekt were formulated in our first report of Nov. 14. 1973. Work was started on Aug. 1. 1973 and during the period under review, a single-cylinder test engine was designed and built and the test facility prepared.

Les travaux relatifs à ce projet de recherche dont les objectifs ont été formulés dans notre premier rapport du 14/11/1973, ont été entamés le 1er août 1973. Au cours de la période du rapport ont été réalisées l'étude décrite brièvement ci-après, et la fabrication du moteur d'essai mono-cylindre, ainsi que la mise en oeuvre du banc d'essai.

Mit den Arbeiten zu diesem Forschungsvorhaben, dessen Zielsetzungen in unserem ersten Bericht vom 14. 11. 1973 formuliert sind, wurde am 1. August 1973 begonnen. Im Berichtszeitraum erfolgten die nachstehend kurz beschriebene Konstruktion und Fertigung des Einzylinder-Versuchsmotors sowie der Aufbau des Prüfstandes.

Als Grundelement für die Ausrüstung des mit einem Hub von 95 mm und einer Bohrung von 90 mm dimensionierten Einzylinder-Versuchsmotors diente ein AVL-Prüfbock, Typ 3, der in seinem Aufbau unserem Versuchsvorhaben zunächst entsprechend angepaßt werden mußte. So waren Maßnahmen zu treffen für den Einbau einer Ölsumpfheizung, für eine Ölspritzkühlung der Kolben, für eine Schmierung der Nocken- und Kipphebelwelle, für eine Spritzölbeaufschlagung der Nockenlaufflächen, für die Ölversorgung der Einspritzpumpen-Leckölsperre und für den Antrieb des Zündstromunterbrechers. Weiterhin mußte ein neues Schwungrad berechnet und angefertigt werden, da die AVL-Schwungscheibe nur für eine Maximaldrehzahl von 4000 U/min ausgelegt war, der Motor aber auch mit höheren Drehzahlen betrieben werden soll.

Die wichtigste und langwierigste Aufgabe der Versuchsvorbereitungen bestand in der Konstruktion und Herstellung der Zylinderköpfe. Da nach unseren bisherigen Erfahrungen die Ladungsschichtung und damit auch die Betriebskennwerte eines FM-Motors durch die Einbaulage der Zündkerze und der Einspritzdüse sehr deutlich zu beeinflussen sind, wurde bei der Gestaltung der Zylinderköpfe die Möglichkeit zu Versuchen mit vier Varianten der Düsen-Kerzen-Anordnung vorgesehen. Mit dem in Bild 1 dar-

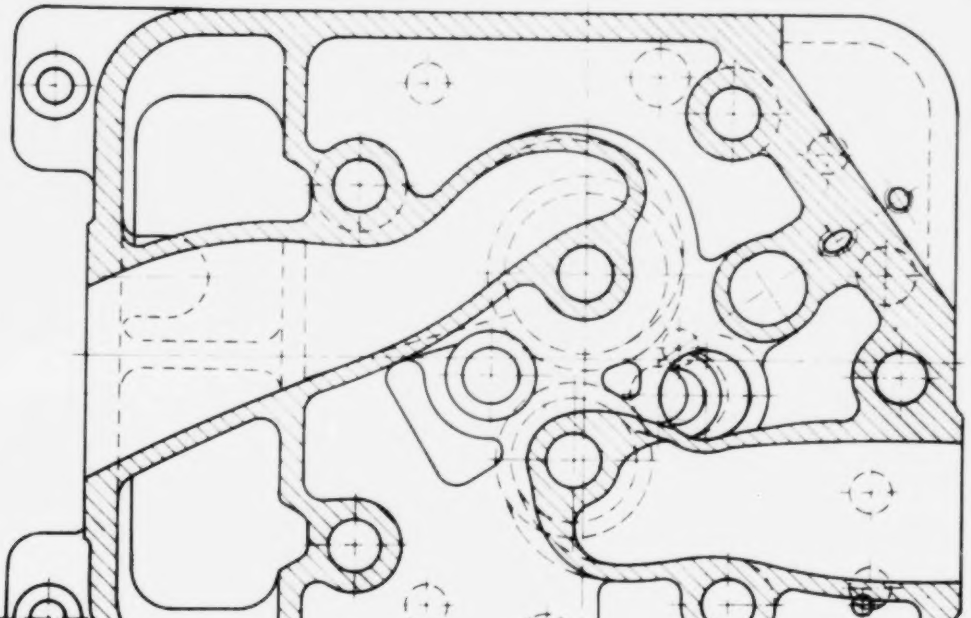

Bild 1, Zweiventil-Zylinderkopf

gestellten Zweiventil-Zylinderkopf können durch Vertauschen der Einbaustellen von Einspritzdüse, Zündkerze und Gasdruckindikator drei verschiedene Düsen-Kerzen-Lagen (A, B, C, siehe Bild 2) erprobt werden. Die vierte Variante D, bei der die ent-

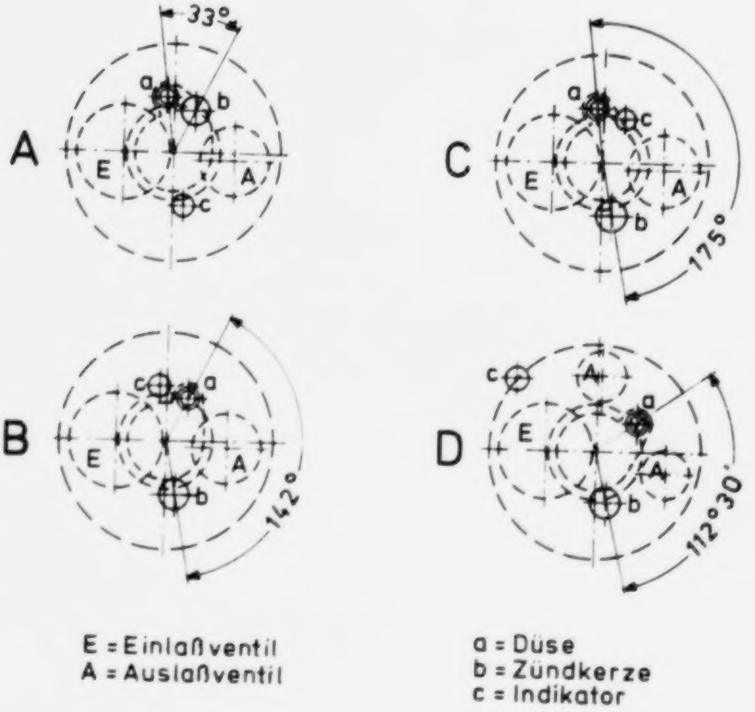

Bild 2, Variationsmöglichkeiten für die Düsen-Zündkerzen-Anordnung

lang des Kolbenbrennraumumfanges gemessene Entfernung der Zündkerze von der Einspritzdüse zwischen den Werten der Versuchsausführungen A und B liegt, wurde mit einer dreiventiligen Zylinderkopfkonstruktion (zwei Auslaßventile, ein Einlaßventil; Bild 3) realisiert. Da mit dieser Düsen-Kerzen-Anordnung bei einem größeren FM-Motor schon sehr gute Betriebsergebnisse erzielt werden konnten, werden unsere Motorversuche auch mit der letzten Variante begonnen.

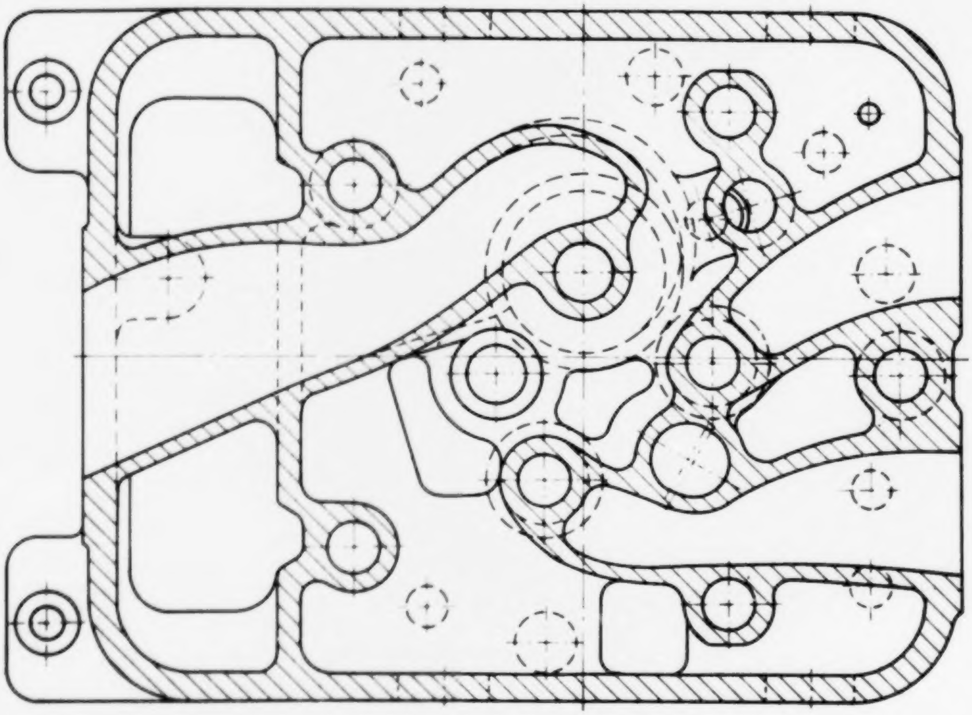

Bild 3, Dreiventil-Zylinderkopf

Für die Strömungsform und für die Intensität des Brennraum-Luftwirbels, das heißt also sowohl für den Vorgang der Ladungsschichtung als auch für den Prozeß der thermischen Gemischbildung und Verbrennung ist die Konfiguration des Einlaßdrallkanals von ausschlaggebender Bedeutung. Um bei den konstruktiv vorgegebenen Einbauverhältnissen eine strömungstechnisch möglichst optimale Kanalführung zu erreichen, mußten deshalb auf einem Drallprüfstand sehr unfangreiche Modellversuche vorgenommen werden. Mit gleicher Sorgfalt war auch die Form des Auslaßkanals zu entwickeln. Nach Abschluß dieser Vorarbeiten konnten dann Gußmodelle und -kerne gefertigt und die Zylinderköpfe abgegossen und bearbeitet werden.

In der Zwischenzeit wurden die Triebwerksteile (Kurbelwelle, Pleuel, Kolben, Zylinderbüchse) und die Ventilsteuerungselemente (Nockenwelle, Stößel, Stoßstangen, Kipphebelbock, Kipphebel, Ventile, Ventilfedern) konstruiert, berechnet und gefertigt. Die Festlegung der Nockenprofile erfolgte in Anlehnung an die Ausführung eines bereits erprobten FM-Vielstoffmotors, wobei jedoch den angestrebten höheren Drehzahlen des neuen Versuchsmotors Rechnung getragen werden mußte. Da für die Auslaßventile des Zwei- und Dreiventilkopfes unterschiedliche Nockenformen erforderlich waren und zudem eine Veränderung des Spreizwinkels zwischen Einlaß- und Auslaßnocken ermöglicht werden sollte, wurde eine zweiteilige, durch Konus und Schraube axial zu verspannende Nockenwelle vorgesehen. Mit einer vielstoffähigen Bosch-Einspritzpumpe, Typ PE2AM, deren zwei Zylinder unterschiedlich bestückt werden können, wurden an einem Einspritzpumpenprüfstand ausführliche Versuche zur Vorauslegung der Einspritzanlage durchgeführt. Mit den zunächst von einem hubraummäßig ähnlichen FM-Vielstoffmotor übernommenen Werten für den Stempeldurchmesser (7 mm), für den Vorhub (2 mm) und für die Nockenerhebungskurve (Bosch-Tangenten-Nocken) wurde mit Rücksicht auf die große Drehzahlspanne des Versuchsmotors in weiten Bereichen der Einfluß des Düsenlochdurchmessers, der Leitungslänge, des Leitungsdurchmessers und des Entlastungsvolumens auf die Spritzdauer, auf den Spritzverzug und auf die Form der Nadelhubdiagramme bei Variation der Einspritzmenge und der Drehzahl ermittelt. Aufgrund der Ergebnisse dieser Messungen wird bei den ersten Motoruntersuchungen eine Einlochdüse mit 0,5 mm Lochdurchmesser, eine Entlastung von 50 mm^3, eine Leitungslänge von 600 mm und ein Leitungsdurchmesser von 1,8 mm verwendet.

Nach der Fertigstellung und Kontrolle aller Versuchsteile wurde der Motor montiert und am Prüfstand aufgebaut. Das Luftansaugsystem wurde sowohl mit einer Kühlanlage als auch mit einer Heizeinrichtung ausgerüstet. Für die später geplanten Aufladeversuche kann es von einem elektrisch angetriebenen Rootsgebläse auch mit Druckluft versorgt werden.

Mit der Installierung aller Meß-, Kontroll- und Bedienungseinrichtungen wurde der Prüfstandsaufbau (Bild 4) abgeschlossen und termingerecht mit der mechanischen Motorvorerprobung begonnen.

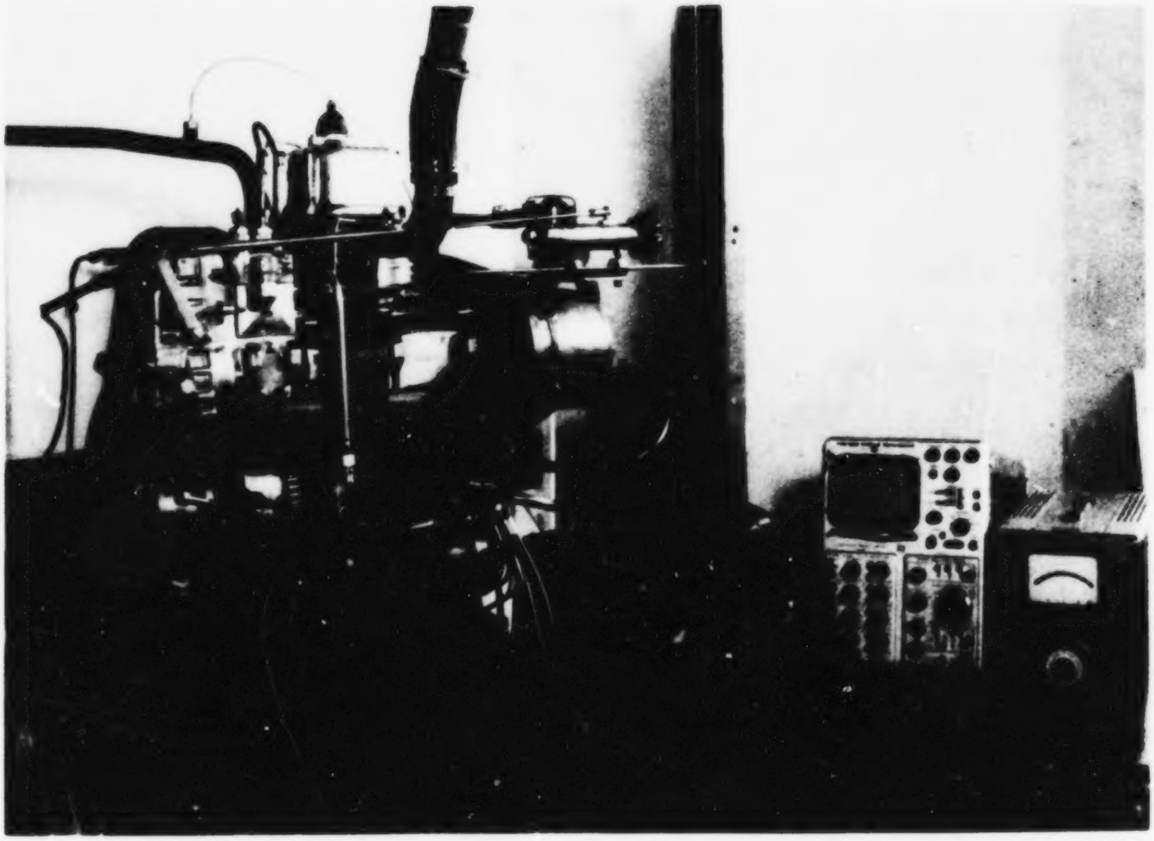

Bild 4, Prüfstandsaufbau

SESSION 3

Advanced Automotive Power Systems

3ème SESSION

Systèmes moteurs avancés pour automobiles

THEMENGRUPPE 3

Neuartige Kraftfahrzeugantriebssysteme

Arbeitsraumbildende Maschinen mit innerer, kontinuierlicher Verbrennung (IKV). *

L. SIENCNIK , J. KEYLWERT
Klöckner - Humboldt - Deutz AG, Köln
P. HOFBAUER , B. WIEDEMANN
Volkswagenwerk AG, Wolfsburg

The continuously poerating internal combustion system in conjunction with expanding volume engines is similar to the gas turbine in that it uses a combustion chamber to feed the mechanical power section. However, the rotating part of the turbo-machine is replaced by an expanding volume engine, such as reciprocating or rotating piston engines. Especially in lower ranges where gasturbines operate less efficiently, will it promise interesting possibilities to control exhaust pollution and noise and to improve efficiency through heat-exchangers.

La combustion interne continuelle avec une machine de volume de travail se sert comme la turbine à gaz avec un cycle ouvert d'une chambre de combustion, qui se trouve hors du rayon du moteur, mais remplace la turbomachine à compression et expansion en des systèmes de moteur à volume. Ceci ouvre des possibilités intéressantes. L' éffectivité à l' aide de la régéneration et d' atteindre un gaz d' échappement ingnoble des éléments polluants et un niveau de bruit bas, speciellement dans les plages de puissance où les turbines à gaz travaillent actuellement peu économique.

Die innere kontinuierliche Verbrennung (IKV) mit arbeitsraumbildenden Maschinen verwendet wie die Gasturbine mit offenem Kreisprozess eine außerhalb des Triebwerkbereiches befindliche Brennkammer, ersetzt aber die Strömungsmaschinen für Kompression und Expansion durch arbeitsraumbildende Triebwerksysteme. Das eröffnet insbesondere in den Leistungsbereichen, in denen die Gasturbine z.Zt. noch unwirtschaftlich arbeitet, interessante Möglichkeiten zu Wirkungsgradsteigerungen durch Regeneration und zur Erzielung eines schadstoffarmen Abgases und geringen Geräuschpegels.

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* gefördert vom Bundesminister für Forschung und Technologie

Die innere kontinuierliche Verbrennung (IKV) mit arbeitsraumbildenden Maschinen verwendet wie die Gasturbine den offenen Kreisprozess mit einer außerhalb des Triebwerkbereiches befindlichen Brennkammer, ersetzt aber die Strömungsmaschine für Kompression und Expansion durch arbeitsraumbildende Triebwerkssysteme.
Die Grundideen zur Realisierung derartiger Maschinen existieren seit längerer Zeit, z.B. von Vogel und K. und E. Wittig (1915), führten aber erst im letzten Jahrzehnt im Zusammenhang mit Fragen des Umweltschutzes und in neuester Zeit durch die Energiekrise zur systematischen Durchforschung von Triebwerkskonzepten und Brennkammern. Auf die Vorarbeiten von Fink (1), Warren und Bjerklie (2) und Rohs (3), sei besonders hingewiesen.
Im Vergleich zur Gasturbine wird erwartet, daß durch die arbeitsraumbildende Maschine die Wirkungsgrade der Teilprozesse insbesondere bei kleinen Triebwerksleistungen günstiger gestaltet werden können und daß das Verdichtungsverhältnis erhöht werden kann, um damit die Leistungsausbeute der Verbrennungsluft anzuheben. Des weiteren werden durch die kontinuierliche Verbrennung im Vergleich zur pulsierenden Verbrennung im Arbeitsraum Vorteile in der Abgasqualität und im Geräuschverhalten erhofft. Im Unterschied zum Otto- oder Dieselmotor muß zur Durchführung der inneren kontinuierlichen Verbrennung die verdichtete Luft aus dem Verdichtungsraum ausgeschoben und das Brenngas aus der Brennkammer wieder in den Expansionsraum zurückgeleitet werden. Die dadurch bedingten prinzipiellen, zusätzlichen Energieverluste und der größere Bauaufwand müssen durch die Regeneration der Abgaswärme und die Gestaltung des Triebwerkes kompensiert werden. Zu dem Zweck wurden vorweg die in Frage kommenden Triebwerke und eine Vielzahl von Brennkammern gesichtet. Einige physikalische Auswahlkriterien sollen hier besprochen werden.

Als Ausgangspunkt soll die Realkreisprozessrechnung genommen werden, die in Bild 1 schematisch gezeigt wird. Der Realkreisprozess wird aus dem idealen Kreisprozess durch Berücksichtigung der Verluste abgeleitet. Im Idealkreisprozess, dargelegt im TS - Diagramm, sind insbesondere zu beachten : daß die Höhe der Prozesstemperatur durch die Abgasqualität begrenzt ist,

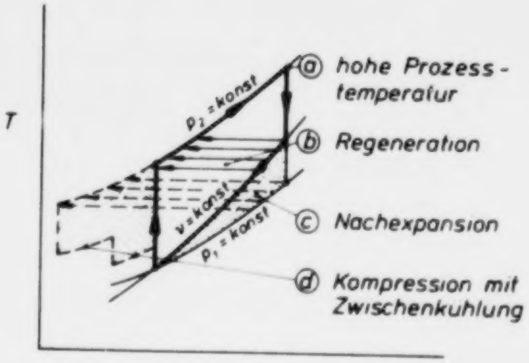


Bild 1

daß eine Regeneration der Abgaswärme durchgeführt wird, und auf eine möglichst vollständige Expansion geachtet werden soll. Die Regeneration kann in beträchtlichem Maße erhöht werden, wenn die Verdichtung durch ein- oder mehrfache Zwischenkühlung sich einer isothermen Verdichtung nähert.

Durch diese Randbedingungen ist die Kreisprozessführung in den Grundzügen vorgegeben. Doch verbleiben noch eine Vielzahl von untereinander abhängigen Parametern, die optimiert werden müssen. Es sei als Beispiel die Abhängigkeit des theoretischen Wirkungsgrades vom Verhältnis des Brennkammerdruckes P_2 zum Aussendruck P_1 für die IKV-tauglichen Kreisprozesse im Bild 2 gezeigt.

Für Kreisprozesse mit Wärmetausch kann der theoretische Wirkungsgrad auf eine einzige Formel zurückgeführt werden:

$$\eta_{th} = 1 - \frac{T_1}{T_5} a$$

Dieser Ableitung lag folgende Vorstellung zugrunde:

Um die Wärmekraftmaschine wird eine Kontrollfläche gezogen und die Qualität der Umsetzung von Wärme-in mechanische Energie auf die Randbedingungen der Außentemperatur T_1 und der Auslaßtemperatur T_5 nach Verlassen des Expansionsraumes bezogen.

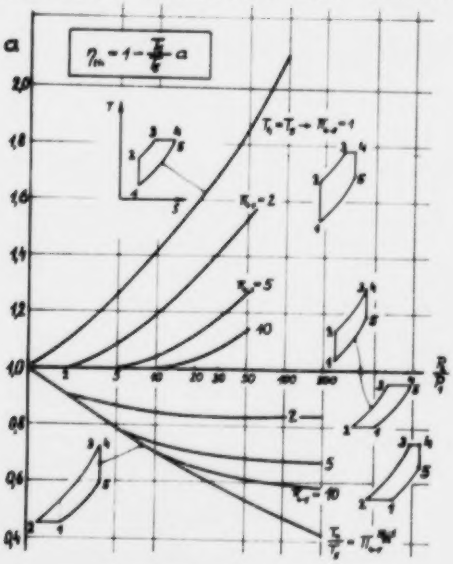


Bild 2

Der Faktor a, der verschiedene Arten der Kreisprozesse charakterisiert, wird in Bild 2 in Abhängigkeit vom Druckverhältnis P_2/P_1 dargelegt. Zunächst ist auffallend, daß für die gegebenen Randbedingungen der theoretische Wirkungsgrad mit steigendem Druckverhältnis je nach Art

der Kreisprozessführung steigen oder fallen kann.
Ein Faktor a>1 gibt eine Verschlechterung des theoretischen Wirkungsgrades mit steigendem Druckverhältnis an. Damit fallen alle im oberen Teil des Diagrammes angegebenen Kreisprozesse für die weitere Betrachtung aus.
Im unteren Teil des Diagrammes sind die Kreisprozesse mit einer isothermen Verdichtung dargelegt. Hierbei ist ein extrem asymmetrischer Kreisprozess auffallend, der nach der isobaren Wärmezufuhr nur noch eine adiabate Expansion aufweist. Sobald eine isotherme vor die adiabate Expansion geschaltet wird, verringert sich der Wirkungsgradzuwachs durch das Expansionsverhältnis P_{4-5} zunehmend. Bei einem adiabaten Expansionsverhältnis von 5 ist die Zuwachsrate in Abhängigkeit vom Druckverhältnis bereits bei einem Druckverhältnis von 1oo kaum noch merkbar. Bei einem adiabaten Expansionsverhältnis von 2 zeigt sich bereits ein klares Minimum beim Druckverhältnis 3o. Die Entscheidung, welche Kreisprozessführung optimal für die gestellte Aufgabe ist, kann nur durch ein umfassendes Rechenprogramm bei Berücksichtigung der gesamten Verluste erstellt werden.
Die vielschichtigen Einflüsse der recht unterschiedlichen physikalischen Vorgänge werden in 3 Hauptgruppen, den idealen Kreisprozess, den Ladungswechselwirkungsgrad und die mechanischen Reibverluste gegliedert. Die Hauptgruppen werden weiter unterteilt, z.B. der Ladungswechsel in Wärmeverluste, Strömungsverluste, Überschiebewirkungsgrad, Leckage und instationäre Gasströmungen. Den Überschiebewirkungsgrad beeinflußt u.a. das Verdichtungsverhältnis, den Totraum und die Aufladung.
Um nicht den Rahmen zu sprengen,wird nur ein Teilergebnis der Realkreisprozessrechnung eines Hubkolbenmotors mit einem Gesamthub von 15o mm und einem Totraum von 1,5 mm kurz besprochen. Der Niederdruckladungswechsel wird entsprechend dem 2-Takt-Prinzip durch Steuerschlitze bestimmter Höhe durchgeführt. In Bild 3 wird das PV-Diagramm für zwei Verdichtungsdrücke von 25 bar und 5o bar bei einer Triebwerksdrehzahl von 28oo U/min gezeigt. Die Überströmquerschnitte für den Hochdruckladungswechsel sind bereits optimiert, dennoch ist die Überschiebearbeit für den Hochdruckladungswechsel merkbar. Im weiteren sei auf den Einfluß des Totraumes hingewiesen. Die im Totraum verbliebene, aber auf 5o bar verdichtete Luft verkürzt den effektiven Hub durch Rück -

expansion um 28 mm. Somit beträgt nach Berücksichtigung der Steuerschlitze der effektive Hub im gegebenen Beispiel nur 72 % des geometrischen Hubes. Beim Senken des Verdichtungsdruckes auf 25 bar werden diese Verhältnisse merkbar besser.

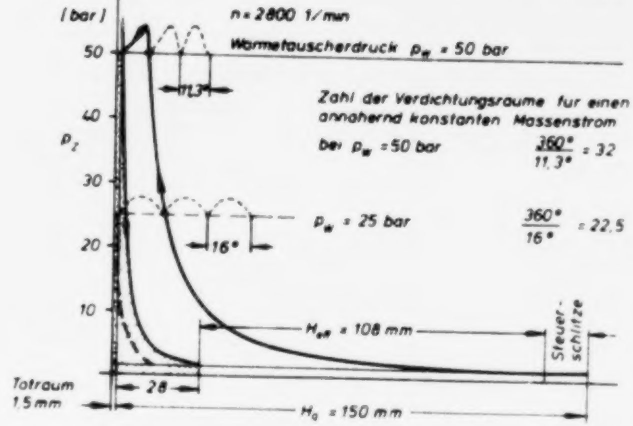


Bild 3

Das vorliegende Beispiel zeigt auch noch eine weitere Eigenart der arbeitsraumbildenden Maschine mit innerer kontinuierlicher Verbrennung: Die Zahl der Verdichtungsräume für einen annähernd konstanten Massenstrom ist stark vom Verdichtungsverhältnis abhängig. Und zwar sind für einen Verdichtungsdruck von etwa 50 bar etwa 32 und bei einer Verdichtung von 25 bar 22 Verdichtungsräume im Idealfall notwendig.

Die hohe Zahl der Verdichtungs- und Expansionsräume engt die Wahl der möglichen Triebwerke erheblich ein. Um dennoch die Auswahl der Triebwerke breiter zu gestalten, ist ein Kompromiß in Richtung zu mehr oder weniger starker Pulsation in der Brennkammer angebracht.

Die Pulsation in der Brennkammer erschwert unter anderem zusätzlich die Entwicklung einer umweltfreundlichen Brennkammer. Z. B. zeigen Berechnungen, die für den vorliegenden Fall einer pulsierenden Brennkammer von Mitarbeitern des Institutes für Angewandte Thermodynamik, Aachen, unter der Leitung von Prof. Pischinger, durchgeführt wurden, folgendes Ergebnis:

Zur Abschätzung des grundsätzlichen Einflusses eines pulsierenden Verbrennungsablaufes auf die NO-Bildung kann die Hochtemperaturzone einer pulsierend arbeitenden Brennkammer in erster Näherung als "instationärer wellstirred-reactor" aufgefaßt werden. Aus dem Diagramm ist in Bild 4 zu ersehen, daß die NO-Bildung durch zunehmende Pulsation des Massenstromes merklich begünstigt wird. Der Rechnung lagen folgende Randbedingungen zugrunde: Die Zeitabhängigkeit des in den Reaktor eintretenden Massenstromes eines Luft-Methangemisches entspricht einer Kreisfunktion mit der Frequenz ω,und der austretende Massenstrom ist

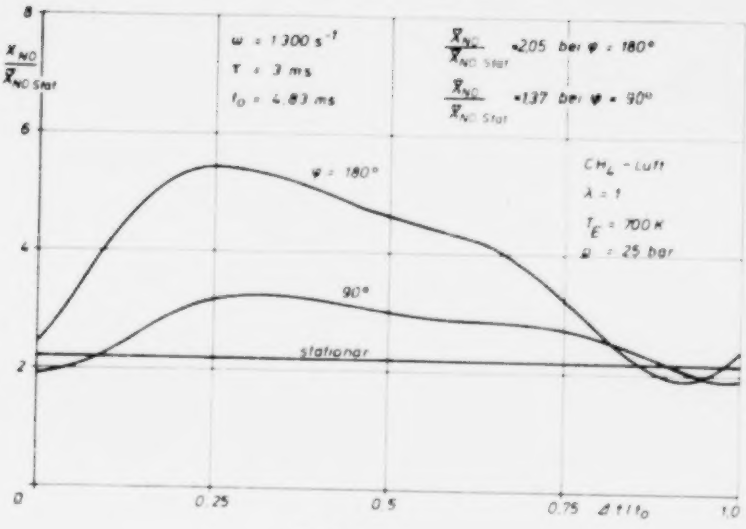
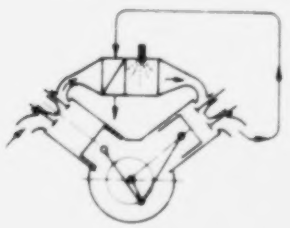


Bild 4

um den Phasenwinkel φ dazu versetzt. Die mittlere Verweilzeit $\tau = \bar{m}/\bar{\dot{m}}$ ist durch die mittlere Masse im Reaktor $\bar{m}$ und den zeitlichen Mittelwert des den Reaktor durchsetzenden Massenstromes $\bar{\dot{m}}$ definiert.
In den beiden Rechenbeispielen wurde gezeigt, daß die im idealen Kreisprozess infolge Abgaswärme-Regeneration und kontinuierlicherVerbrennung gegebenen Vorteile empfindlich gemindert werden können. Dennoch werden bei optimaler Gestaltung der Bauteile Vorteile erwartet .
Im weiteren werden 5 Triebwerksarten und zwei Brennkammertypen vorgestellt, die von der IKV-Arbeitsgemeinschaft KHD-VW einer näheren Studie unterzogen wurden .
Zunächst können alle IKV-tauglichen Triebwerke in zwei Kategorien geteilt werden (siehe Bild 5).

I Arbeitsraume und Brennkammer stehen



II Arbeitsraume oder Brennkammer rotieren

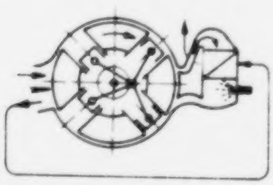


Bild 5

I. Die Arbeitsräume und Brennkammer stehen. Jeder Arbeitsraum muß durch eine Zu- und Ableitung für das Arbeitsgas mit der Brennkammer verbunden werden.Je nach Bauart sind sehr kurze Dichtlängen möglich,dann aber ist eine Vielzahl von Steuerorganen nötig.

II. Die Arbeitsräume oder Brennkammer rotieren. Diese Bauart kommt der IKV-Forderung prinzipiell dadurch entgegen, daß sie die arbeitsraumbildenden Organe an den Ein- und Auslaßöffnungen vorbeistreichen läßt und damit nicht nur eine Selbststeuerung, sondern auch sehr kurze Leitungen ermöglicht. Ein gravierender Nachteil sind die langen und bewegten Dichtgrenzen.

Triebwerke

Von den 5 zur näheren Untersuchung ausgewählten Triebwerken sind die Bauarten : Hubkolbenmotor und Kämmeingriffsmaschine in die Gruppe I einzuordnen; die Bauarten : Zellenmaschine, Kreiskolbenmotor Hubeingriff und der Axialkolbenmotor unter die Gruppe II zu zählen.

Zellenmaschine

Von allen in der letztgenannten Gruppe aufgezählten Triebwerken kommt die Zellenmaschine der Forderung nach einer Vielzahl von Arbeitsräumen am nächsten. Aber sie läßt auch die größten Schwierigkeiten bei der Gestaltung der Dichtelemente vermuten. Dazu wurde eine Studie von möglichen Zellenmaschinen-Bauarten durchgeführt, die in Bild 6 skizziert sind :

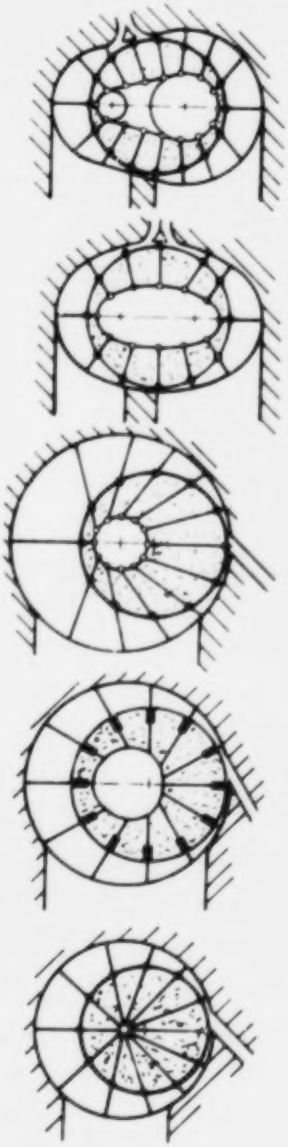


Bild 6

Typ 1 ermöglicht ein 4-Takt-Prinzip, das eine langsame Verdichtung mit genügend Zeit für die Abfuhr der Verdichtungswärme und eine kurze Expansionszeit erlaubt. Die kinematischen Bedingungen hierzu lassen sich zur Zeit technisch nicht lösen.

Typ 2 erlaubt auch noch einen 4-Takt-Betrieb, aber die Kompression und Expansion sind symmetrisch . Die kinematische Vereinfachung, indem die Flügel auf einerEllipse mit konstanter Umfangskraft geführt werden, verbessert die Durchführbarkeit nicht entscheidend.

Beim Typ 3 ist im Vergleich zum Typ 2 die Flügelaufhängung von einer Ellipse zum Kreis vereinfacht worden. Dies bewirkt nur noch einen oberen Totpunkt pro Umdrehung und dadurch ist ein 4-Takt-Betrieb mit einem Triebwerk nicht mehr möglich. Die Flügel ändern wie bei den Typen 1 und 2 während einer Umdrehung sowohl am Innen- als auch am Außenkreis laufend den Durchdringungs- bzw. Berührungswinkel. Dies erschwert erheblich die Abdichtung . Typ 4 ist der normale Zellenradverdichter. Dabei bleiben die Flügel bei einem Durchdringungswinkel von 9o° am Innenkreis orientiert. Am Außenkreis findet eine Abwälz-

und Gleitbewegung statt, hingegen ermöglichen die Seiten der Schieber Spaltdichtungen.
Typ 5 erlaubt auch am Außenkreis Spaltdichtungen, verlangt aber senkrecht zum Außenkreis orientierte Flügel. Die Durchdringung des Innenkreises fordert Schwenk-Schiebedichtungen. Für den Typ 5 werden Konstruktions- und Bauteiluntersuchungen durchgeführt.

Kreiskolbenmaschine mit Hubeingriff

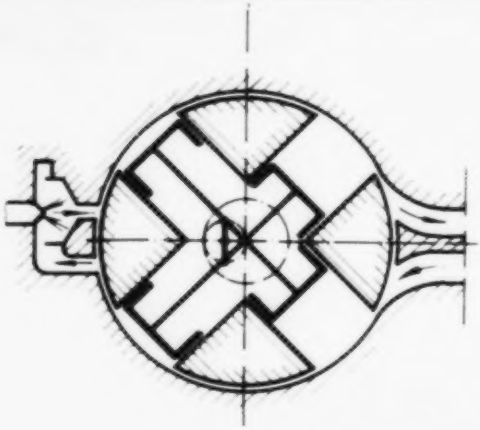


Bild 7

Die im Bild 7 gezeigte Kreiskolbenmaschine erlaubt einen vollkommenen Massenausgleich, da alle umlaufenden Teile eine reine Rotationsbewegung ausführen. Um ein Klemmen des Triebwerkes zu verhindern, wird mittels eines Zahnradpaares eine Zwangsführung zwischen Excenter und Gehäuse erzielt. Der Hubeingriff erlaubt im Vergleich zu anderen Rotationskolbenmaschinen weitgehend die Verwendung bekannter Bauteile und Dichtelemente. Die Abdichtung der Arbeitsräume in Form von Kolben und Kolbenringen dürfte beherrschbar und betriebssicher sein. Probleme bereitet die Abdichtung der Brennkammer bzw. die Abdichtung am Umfang des rotierenden Zylindergehäuses.

Axialkolbenmotor

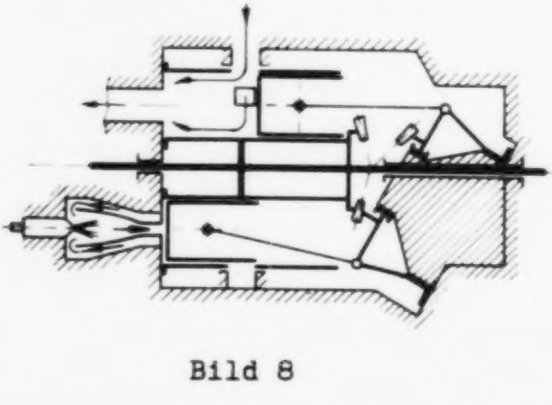


Bild 8

Axialkolbenmaschinen mit Taumelscheibenantrieb bieten sich durch die Anordnung vieler Zylinder um die Mittelachse als 2-Takt-Motor für das IKV-Verfahren an. Die im Bild 8 skizzierte Bauart mit rotierendem Zylinderblock enthält an der Trennstelle zwischen den umlaufenden Arbeitsräumen und einer im Bereich des oberen Totraumes im feststehenden Zylinderkopf angeordneten IKV-Brennkammer eine typbedingte Drehschiebersteuerung mit idealen Voraussetzungen für große Querschnitte und kurze Steuerzeiten (3). Diesen Vorteilen steht in der großen Fläche ein nur schwer lösbares Abdichtproblem mit hohen Umlaufgeschwindigkeiten und Reibverlusten gegenüber.

Hubkolbenmotor mit zusätzlichen Steuerelementen

Mittels zusätzlicher Steuerelemente läßt sich der Hubkolbenmotor als Maschine mit innerer kontinuierlicher Verbrennung verwenden. (siehe Bild 9) Dabei werden die Steuerelemente thermisch und mechanisch hoch beansprucht. Zusätzlich wird für Maschinen, die im Split-Cycle, Warren (2), arbeiten, der Expansionsteil ausschließlich mit Heißgas beaufschlagt. Es wurde daher eine Steuerung entwickelt, bei der Kompression und Expansion im selben Arbeitsraum stattfinden, d.h. die Steuerelemente und der Arbeitsraum werden durch das Frischgas gekühlt. Durch die Wahl einer kombinierten Schieber-Ventil-Steuerung sollen die mechanischen und thermischen Probleme beherrscht werden, dabei werden die für Steuerung zur Verfügung stehenden Zeiten im Vergleich zum Ventiltrieb verdoppelt. Um die Kosten und das Entwicklungsrisiko niedrig zu halten, wurde als Hubkolbenmotor ein produktionsreifer 6-Zylinder - 2-Takt-Motor mit 12oo cm^3 Hubraum gewählt. Für grundsätzliche Untersuchungen kann das Triebwerk nach Adaptierung der Steuerelemente weitgehend unverändert übernommen werden.

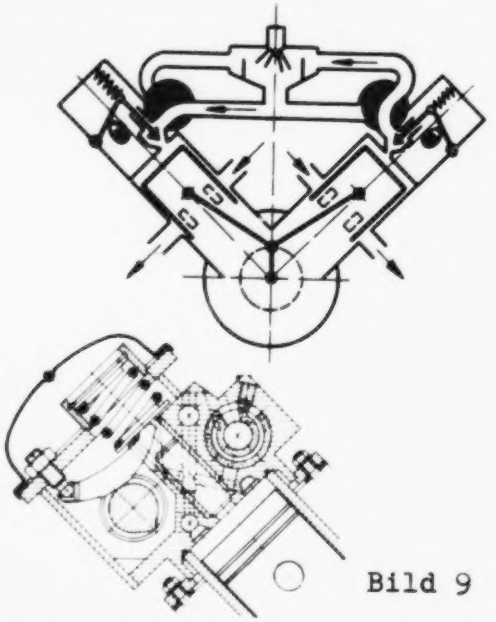


Bild 9

Kämmeingriffsmaschine

Es handelt sich vom übergeordneten Bauprinzip her um einen Rotationskolbenmotor der Trochoiden-Bauart mit Kämmeingriff (4),(5). Er wird als 4-Takt-Motor mit vom Kolben selbst gesteuerten Niederdruck-Ladungswechsel angewandt. ((6)und Bild 1o) Diese Steuerung genügt zur Durchführung einer konventionell pulsierenden Verbrennung. Zur Verwirklichung des IKV-Prozesses muß noch zusätzlich die Steuerung des Austausches der Hochdruckladung sicher-

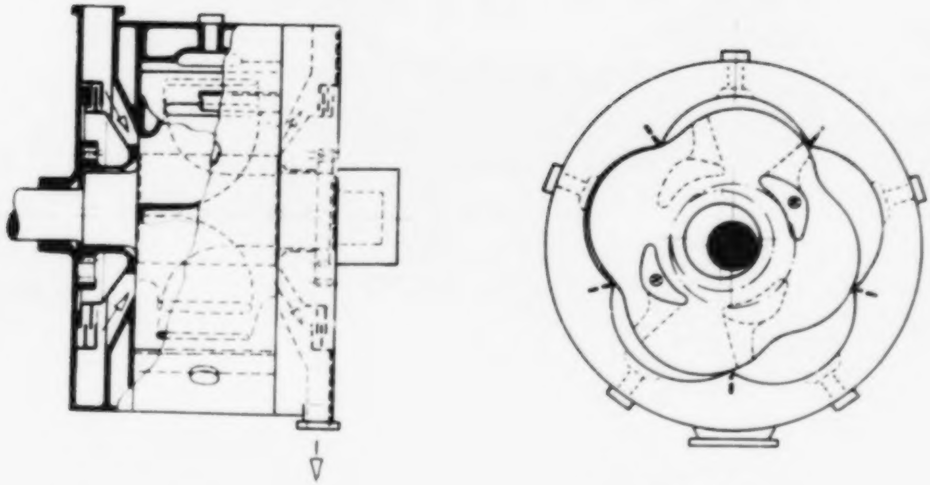
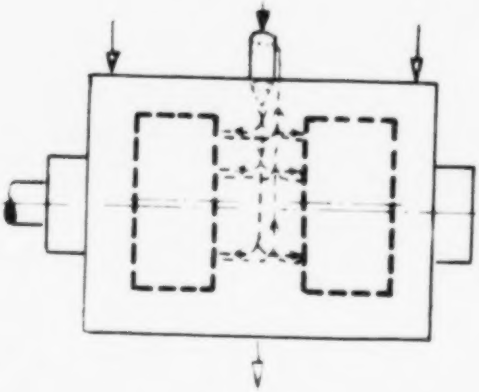


Bild 1o



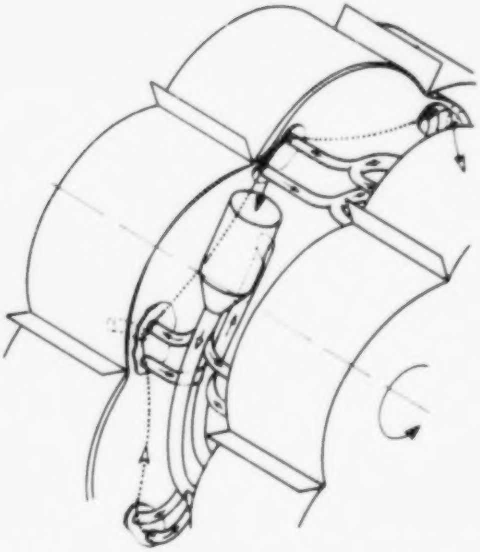
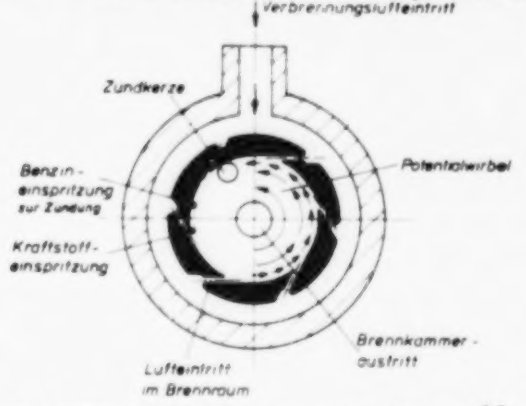


Bild 11

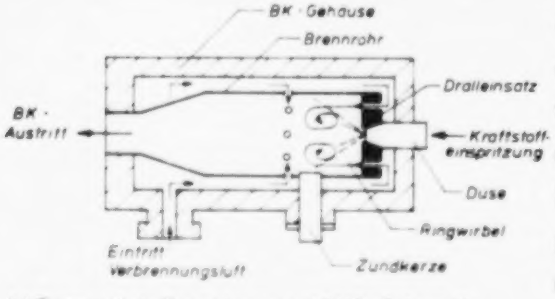
gestellt werden. Sie erfolgt ebenfalls durch den sich drehenden und gleichzeitig sich abwälzenden Kolben selbststeuernd über Öffnungen in einer Seitenwand des Kolbens und Kanäle im Kolben, die ständig Verbindung mit dem Arbeitsraum haben (Bild 11).Die Verbindung zur im Gehäuse angeordneten feststehenden Brennkammer und zurück zum ebenfalls feststehenden Arbeitsraum wird durch zwei nebeneinanderliegende Steueröffnungen für jeden Arbeitsraum in der Seitenwand des Gehäuses über ein entsprechend ausgebildetes Verteilungssystem hergestellt, in dem diese feststehenden Öffnungen von den bewegten Gasöffnungen in der Kolbenseitenwand zeitlich aufeinanderfolgend überschliffen werden (7). Dabei müssen diese mit Steueröffnungen besetzten Zonen der Gehäuseseitenwand gegenüber dem Niederdruckraum entsprechend abgedichtet werden. Im Verteilersystem sind Mittel für den regenerativen Wärmeaustausch vorgesehen. In der gezeigten Ausführungsform mit einer Twin-Anordnung der Kolben lassen sich diese Forderungen konstruktiv mit relativ einfachen Mitteln und raumsparend verwirklichen.

Brennkammerentwicklung

Zur Zeit werden im Rahmen des IKV-Programmes zwei Brennkammern untersucht und entwickelt. Das Entwicklungsziel ist eine Brennkammer, die im quasi-stationären Betrieb bei möglichst hoher Brennkammeraustrittstemperatur ein sauberes Abgas liefert.



a) Potentialwirbel-Brennkammer nach Fink [1]



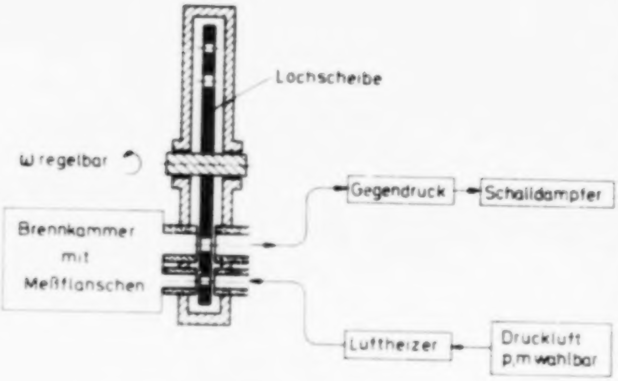
b) Ringwirbel-Brennkammer (KHD-Entwurf)

Bild 12

Die in Bild 12a dargestellte Potentialwirbelbrennkammer ist bei Fink (1) beschrieben. Bei der DFVLR ist diese Brennkammer einer Funktionsprüfung unterzogen worden. Bild 12b zeigt eine bei KHD entwickelte Ringwirbelbrennkammer. Durch einen Drallkörper wird in Verbindung mit den Sekundärluftbohrungen ein Ringwirbel erzeugt. Mit dieser Brennkammer liegen erste Versuchsergebnisse im stationären Betrieb mit nicht vorgewärmter Luft bei 1o bar Betriebsdruck vor.

Zur Zeit werden Zünd- und Brenngrenzen sowie das Regelverhalten der Brennkammer untersucht. Außerdem werden erste Abgasanalysen durchgeführt. Stationäre Brennversuche bei Betriebsdruck 3o bar und mit vorgeheizter Luft ($t \leq 5oo^{o}$ C) sind in Vorbereitung. Beim Übergang zu höheren Temperaturen kann es notwendig werden, das Brennrohr aus Keramik fertigen zu lassen.

Da die vorgestellten IKV-Triebwerke der Brennkammer die Luft mehr oder weniger pulsierend zuführen, und da das Heißgas pulsierend abgenommen wird, ist das Verhalten der Brennkammer im pulsierenden Betrieb zu untersuchen. Dazu ist im Institut für Angewandte Gasdynamik der DFVLR in Porz unter der Leitung von Herrn Prof. Heyser der in Bild 13 skizzierte Prüfstand für



Brennkammer-Prufstand f pulsierende Verbrennung bei der DFVLR-Porz

Bild 13

Brennkammer-Untersuchungen aufgebaut worden. Die Pulsation der Zuluft und des Heißgases werden mit einer Lochscheibe simuliert. Die verschiedenen Überschiebegesetze der einzelnen Triebwerke werden durch Art und Anordnung der Löcher auf der Scheibe, sowie durch Variation der Drehzahl simuliert. Es können Drücke bis 60 bar und Brennkammereintrittstemperaturen bis über 1000° C gefahren werden. Der Abgasgegendruck wird mit einer Drosselklappe eingestellt.

Die Qualität des vom IKV-Motor abgegebenen Abgases hängt stark vom zeitlichen Verlauf des Druckes und der Temperatur bei der Expansion des von der Brennkammer gelieferten Heißgases ab. Diese Expansion ist mit einer Lochscheibe nicht zu simulieren, sie muß in einem der ausgewählten Triebwerke erfolgen. Als erstes Triebwerk wird ein Flügelradexpander für diese Versuche zur Verfügung stehen.

Die konstruktiven Studien der 5 Triebwerke mit Bauteiluntersuchungen und Realkreisprozessrechnungen einerseits, und die Brennkammerversuche bei stationärem und pulsierendem Betrieb andererseits, sollen bis Ende März 1975 soweit abgeschlossen sein, daß die Entscheidung möglich wird, ob der arbeitsraumbildende Motor mit IKV in den achtziger Jahren den klassischen Hubkolbenmotor in wesentlichen Anwendungsbereichen übertreffen kann. Bei positiver Antwort wird die Entwicklungskapazität auf die erfolgversprechendste Variante des Triebwerkes und der Brennkammer konzentriert. Eine negative Antwort würde kostspielige Fehlentwicklungen vermeiden. Darüber hinaus kann aufgrund der bisherigen Arbeiten schon jetzt übersehen werden, daß eine Reihe von Erkenntnissen dieser Studien auch die Entwicklung der Motoren mit einer Verbrennung im Arbeitsraum befruchten wird.

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"PROGRESS OF ROTARY ENGINES, TYPE NSU/WANKEL"

to be reported
by

Dr.-Ing. Albrecht Hartmann

AUDI NSU AUTO UNION Aktiengesellschaft

Neckarsulm

on 5th November 1974

at 2nd NATO/CCMS-SYMPOSIUM

to be held

from 3rd to 8th November 1974

at Düsseldorf

189

Zusammenfassung

Der Kreiskolbenmotor, System AUDI NSU/WANKEL, konnte in den vergangenen 2 Jahren verbrauchsseitig entscheidend verbessert werden. Für die Produktion bestimmte KKM haben heute gegenüber Hubkolbenmotoren gleichwertige Verbräuche.

Die Erfüllbarkeit der US-Abgasgesetze 1977 wurde mit Prototypen-Motoren bei guten Verbräuchen nachgewiesen. An Verbesserungen für die weitere Reduzierung der Produktionskosten wird gearbeitet.

Eine neue Generation von KKM-Ladungsschichtungsmotoren befindet sich im fortgeschrittenen Entwicklungsstadium.

Summary

In the past two years, the rotary engine, system AUDI NSU/WANKEL, has considerably been improved with regard to fuel consumption. Rotary engines scheduled for production have at present fuel consumption data comparable to reciprocating engines.

The required 1977 US emission data have been proved by prototype-engines with a low fuel consumption. Development work for improving production cost is being continued.

A new generation of rotary engines with stratified charge is in an advanced stage.

Résumé

Au cours des deux années passées, il a été possible de réduire considérablement la consommation de combustible du moteur rotatif, système AUDI NSU/WANKEL. Les moteurs rotatifs destinés à la production ont à présent une consommation de combustible, comparable à celle des moteurs classiques.

Il a été prouvé par des moteurs-prototypes à une basse consommation de combustible, qu'il est possible de réaliser les prescriptions des Etats Unis pour 1977, concernant le gaz d'échappement. On continue de faire des efforts, pour réduire encore plus les frais de production.

Une nouvelle génération des moteurs rotatifs à charge stratifiée est dans une phase de développement avancée.

1.) Introduction

The rotary engine, system NSU/WANKEL, is one of the youngest and most promising alternatives to the well known reciprocating engine which is more than 100 years old. The rotary engine, since 1953 under industrial development, has the following world-wide accepted advantages compared with the present conventional engines:

a) - Less vibration,
   - smooth running,

b) - lower weight,
   - lower volume,
   - less parts
     and herewith the potential for lower production cost.

Due to the relatively short development time, the production number of more than 750 000 automotive rotary engines has to be respected.

An expected high development potential can be concluded from experience and the results of pre-tests founded by measurements on prototypes.

Figure 1 shows the known function of growth applicable to any technical development of the status of the art over development time. The progress of prototype engines and the status of pre-tests compared with production engines are obvious.

2.) Improvement of fuel consumption

Rotary engines being in production have been blamed for their high fuel consumption level, especially since politicians speak of an energy crisis.

AUDI NSU and their qualified licensees have proved with a great number of prototype engines that there is an important fuel consumption improvement up to 28 %, especially in the critical low end range, as shown in fig. 2.

Fig. 3 shows that the specific fuel consumption of those prototype rotary engines is already in the most frequent driving condition area better than that of the present reciprocating engines.

For comparison: Fig. 3 shows also the specific fuel consumption over the brake mean effective pressure for production rotary engines.

One of the most important factors for s.f.c. improvement in the rotary engine will be a better gas tightness.

Fig. 4 shows the influence of the gas leakage area on s.f.c. at part load, for instance, the s.f.c. will be increased by 15 % at 2000 r.p.m. for a gas leakage area of 2 mm^2 per chamber, compared with a completely gas-tight engine. The corresponding figure for 4000 r.p.m. would be 10 % only. This means that the gas-tightness is of greater importance at a lower engine speed.

The same tendency refers to the influence of gas leakage on brake mean effective pressure and compression (fig.5).

A low wear rate of the sealing grid is imperative for getting a gas leakage as low as possible during the whole engine life.

In this respect, AUDI NSU made a great progress by applying the suitable material which guarantees an extremely low apex seal tip wear (fig. 6).

The wear of apex seal in axial direction has a greater influence on gas leakage. The amount of leakage can be influenced by the specific design of the apex seal. Fig. 7 shows the axial wear depending on running distance of two advanced 3-piece apex seal designs. The one seal with an interrupted tip line and long end pieces, compared with the other one with a uninterrupted tip line, shows a very small wear rate in axial direction. This type of apex seal is to some extent self-adjusting.

1-, 2- and 3-piece apex seals wear very differently. For a higher axial wear rate we have a higher leakage and thus a decrease of the brake mean effective pressure. Fig. 8 shows the brake mean effective pressure over engine speed for 1-, 2- and 3-piece apex seals. The 2-piece apex seal has an uninterrupted tip line. The 3-piece apex seal has an interrupted tip line. After a longer running time, the 3-piece apex seal shows the best results: It still remains at high brake mean effective pressure level, whilst the 1-piece apex seal shows the highest drop of mean effective pressure, especially at low engine speed.

The wear is, of course, influenced by the wear partners. Different wear partners have different friction coefficients. A low friction coefficient is desirable for small friction losses. Fig. 9 shows an example of the influence of 3 wear partners on kinetic friction as a function of load. The wear partner 3 is superior to the remaining 2 wear partners: It has the lowest friction coefficient which is nearly independant of load.

3.) Status of exhaust emission control.

As it is known, the rotary engine has - due to delayed combustion - on the one hand the disadvantage of a higher HC emission of the basic engine and on the other hand the advantage of a much lower NO_x emission, compared with the reciprocating engine. Fig. 10 shows

- the HC emission of the basic engine (dotted line),
- the HC emission behind production reactor (full line),
- the HC emission for an improved reactor system (dot-dash line).

The emission data shown are applicable to the first cycle of the European test, which has the highest percentage of unburned emission.

In Fig. 11 the reduction of CO by the 2 different designs of reactors is demonstrated. The CO emission of the rotary engine is not as severe as the HC emission.

For the after-treatment of the emission a high exhaust gas temperature is desirable. The rotary engine has, compared with the reciprocating engine, the advantage that the exhaust temperature is 100 to 150°C higher at part load and full load (fig. 12).

4.) Relation between fuel consumption and exhaust emission.

The fuel consumption level has been increased between 15 and 21 %. in the most frequent driving condition area, by applying an exhaust emission control system (fig.13), consisting of a thermal reactor. The reason for this increase of fuel consumption is:

- a necessary rich carburator mixture,
- a higher exhaust gas back-pressure,
- retard ignition for quicker heating up the after-burning device.

The data in fig. 13 are given for an engine speed of 2000 1/min and plotted over brake mean effective pressure.

In order to avoid an increase of fuel consumption by using a thermal reactor in connection with a rich air/fuel mixture, it is desirable to switch from a rich concept with secondary air injection to a lean concept without secondary air injection. In fig. 14 are shown 4 different diagrams:

- In the first diagram the HC emission over air fuel ratio is shown. The full line is for the rich concept, the dotted line for a lean concept. Should it be possible to realize the lean concept, the HC and CO emissions could be kept on the same low level as with the rich concept.

- Only with respect to NO_x emission the lean concept shows, according to the present preliminary results,a small increase which is insignificant due to the low level.

- At a combustion with excessive air best efficiency can be reached. In the lower diagram (fig.14)the fuel consumption is plotted again over the air/fuel ratio for the rich and lean concepts. With respect to drivability we have to consider a certain range of air/fuel ratio for both cases, the rich and the lean concepts. For the lean concept, you receive a considerably better fuel consumption, compared with the rich concept.

It has already been demonstrated with 4 rotary engines of 4 different automotive companies that the US 1977 standards can be fulfilled. The HC, CO and NO_x emissions of the new engine are considerably below the given limits. Diagram 15 includes also the emission of the Honda CVCC reciprocating engine which is one of the leading concepts of the present reciprocating engines.

In fig. 16 the milege is plotted over the inertia weight of the car. The diagram contains 2 lines:

- The average values of the different 1957 to 1967 American cars,
- the decreased milege of the average 1973 American cars; the milege is decreased due to the necessary emission requirements.

In comparison with these curves, the range of milege of rotary engine powered cars with an inertia of 3000 pounds is to be respected, especially with regard to the effect that these engines are emission-controlled for the 1977 American standards. These data underline the development potential of the rotary engine.

5.) Stratified charge rotary engine, system AUDI NSU/ WANKEL.

The best specific fuel consumption demonstrated by rotary engines has been achieved with stratified charge. In fig. 17 the results gained by our licensee Curtiss-Wright a few weeks ago are shown.*) The diagram shows the s.f.c. values over mean effective pressure. The diagram contains 4 curves:

- Full line represents the reciprocating automotive engine.
- The curve in close contact with the full line represents an earlier carburated rotary engine.
- The lowest line shows the s.f.c. data of the Curtiss-Wright stratified charge rotary engine with shower head nozzle.
- The specific fuel consumption at 2000 1/min of this engine could be further improved at a very low mean effective pressure by pilot injection system.

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*) (published in
(SAE Paper No. 741206)

The pilot injector in connection with the spark plug is shown in fig. 18.

6.) Conclusion

Up to now the rotary engine has been the most successful alternative to the reciprocating engines. When taking into consideration the necessity of saving fuel and material on a world-wide basis, the rotary engine gives the future car designer the possibility of coming to more compact cars without a decrease of passenger space and comfort. The rotary engine has a smaller installation volume than comparable reciprocating engines and a much smaller installation volume than the other alternatives: gas turbine and Stirling engine.

Like all important technical developments, the rotary engine does not make winning streak without "back kicks".

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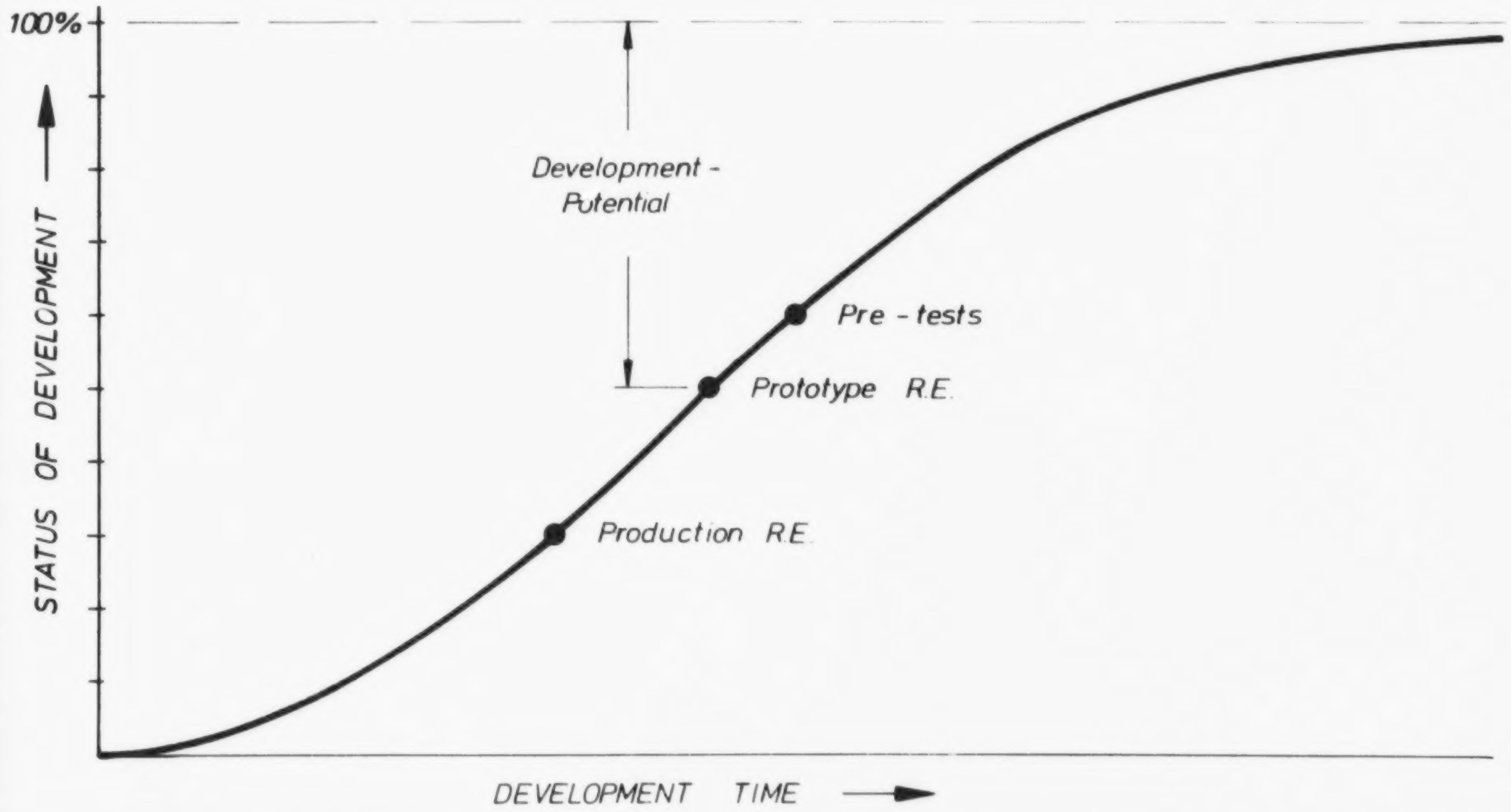
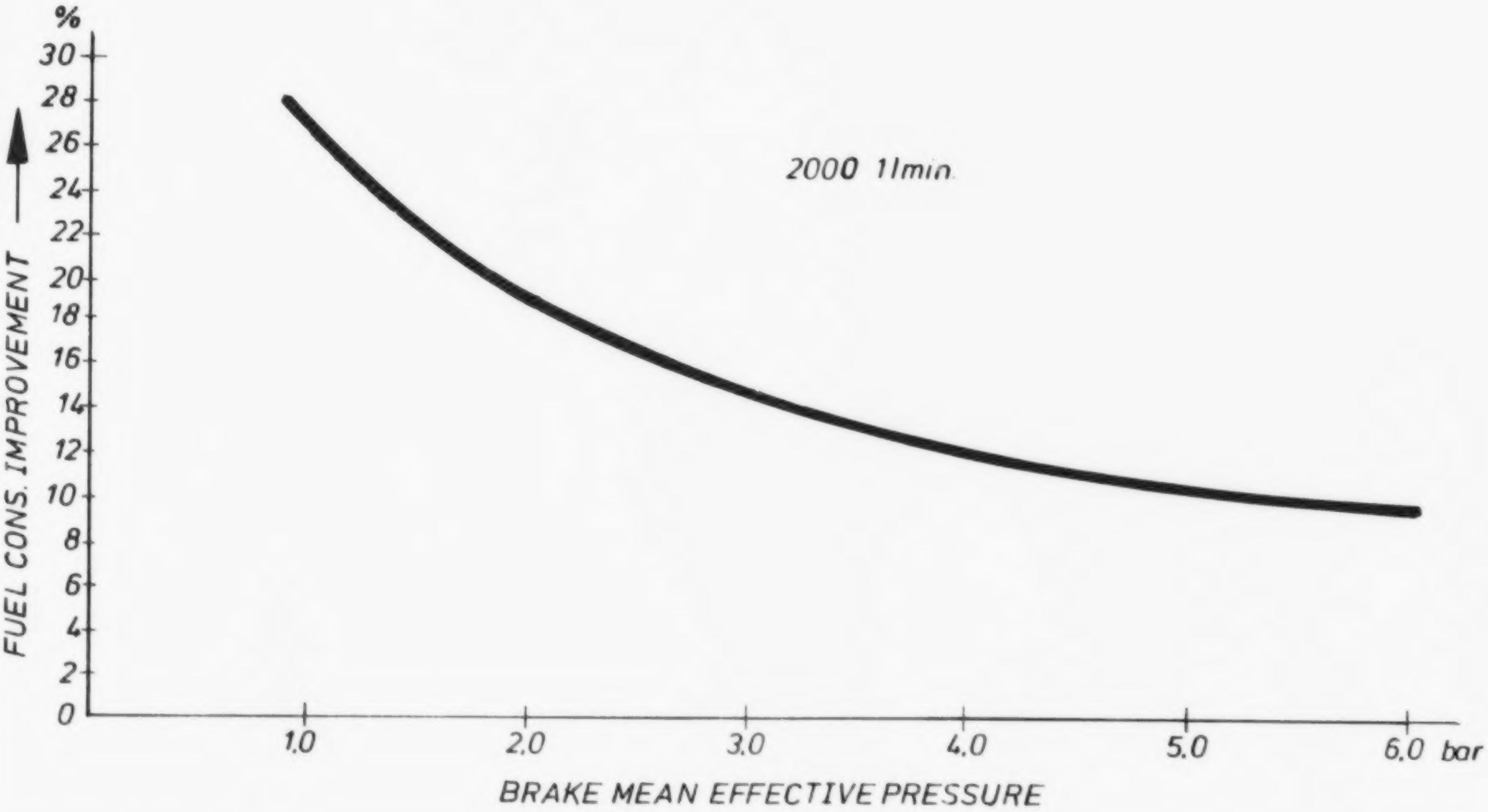


AUDI NSU

R.E. DEVELOPMENT POTENTIAL

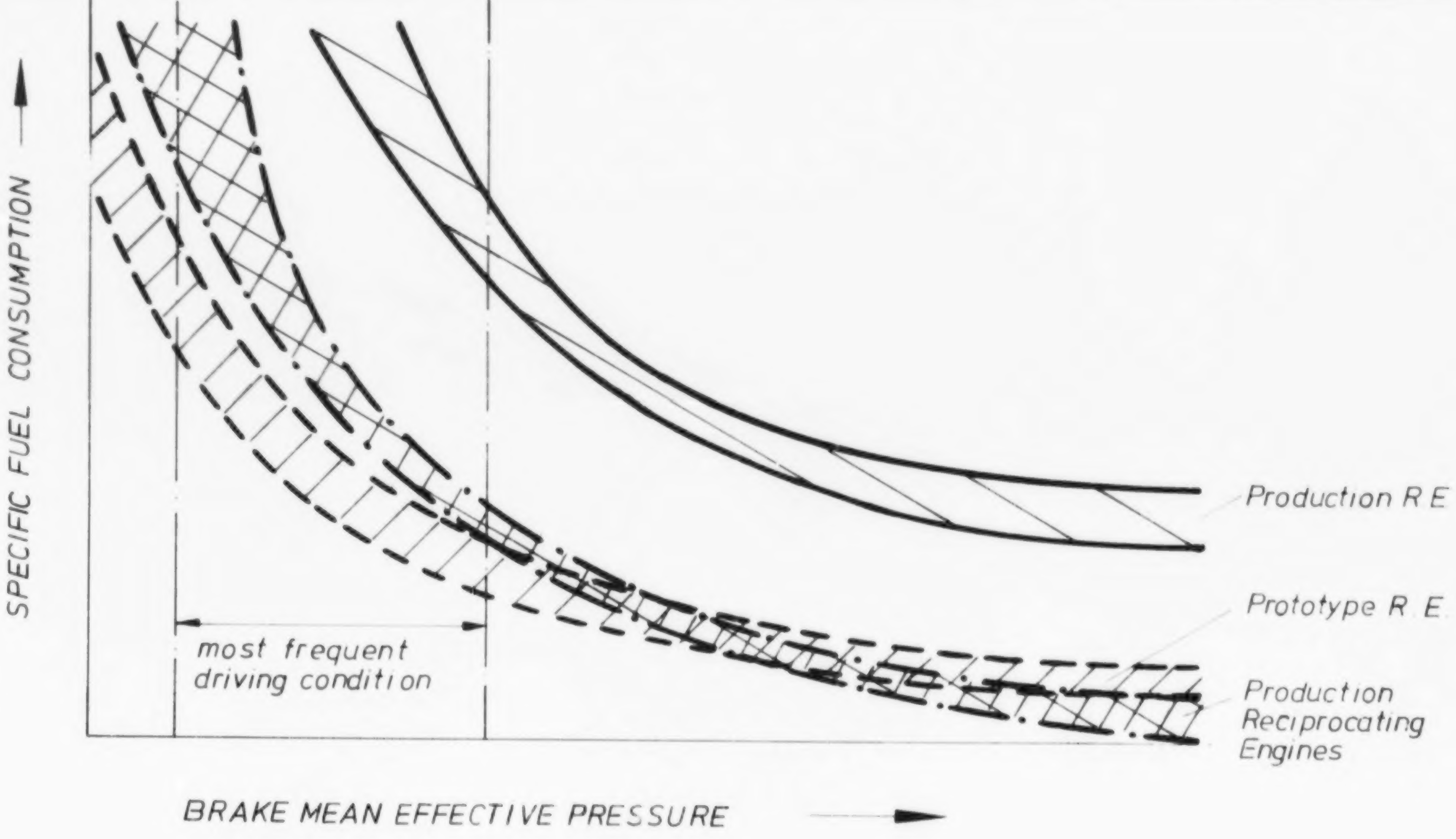
Fig. 1



AUDI NSU

FUEL CONSUMPTION IMPROVEMENT OF EXPERIM. R.E.
COMP. TO MASS PROD. R.E.

Fig. 2



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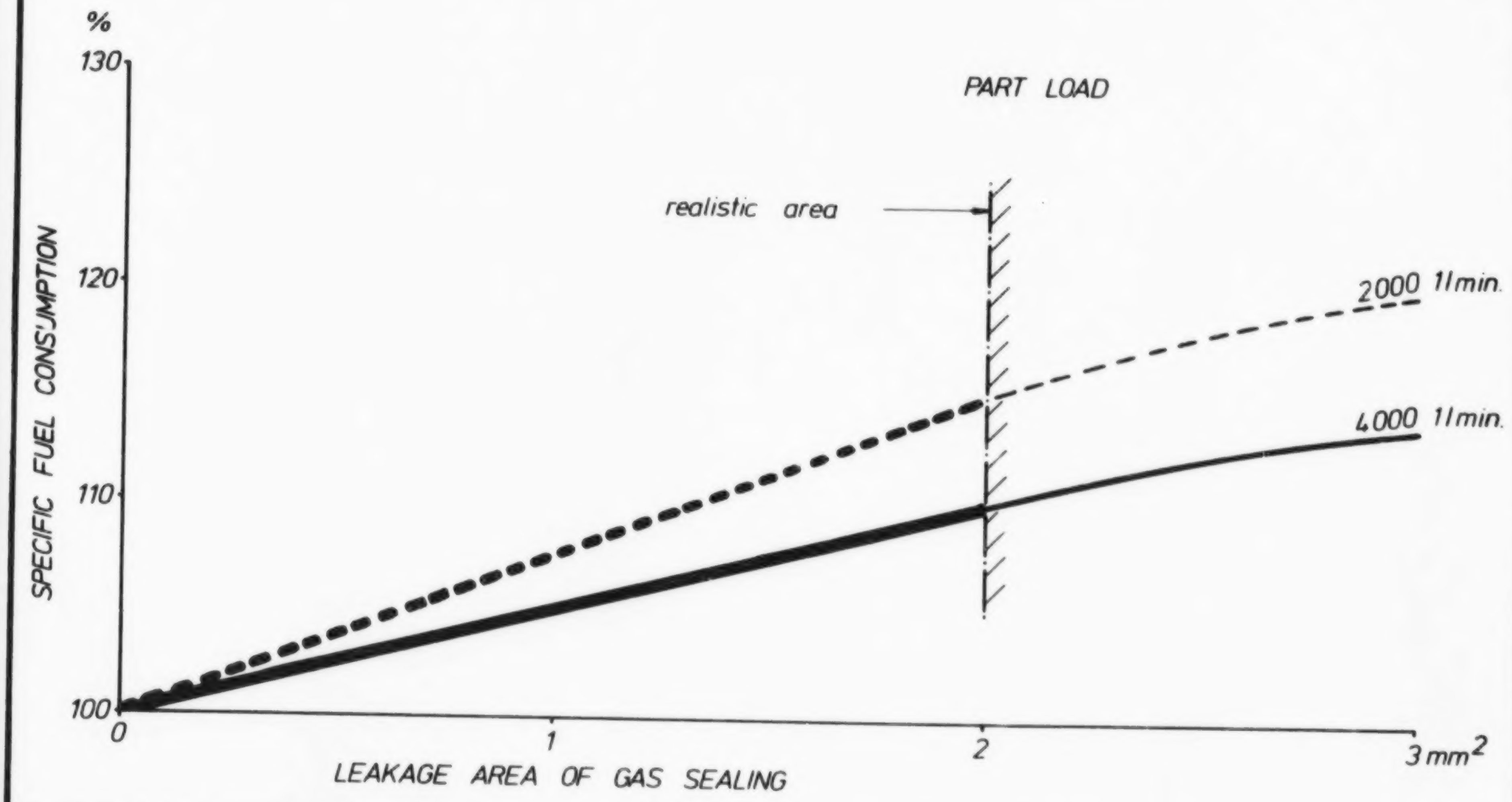
SPECIFIC FUEL CONSUMPTION OF R.E. AND RECIPRO. ENGINES, 2000 1/min.

Fig. 3



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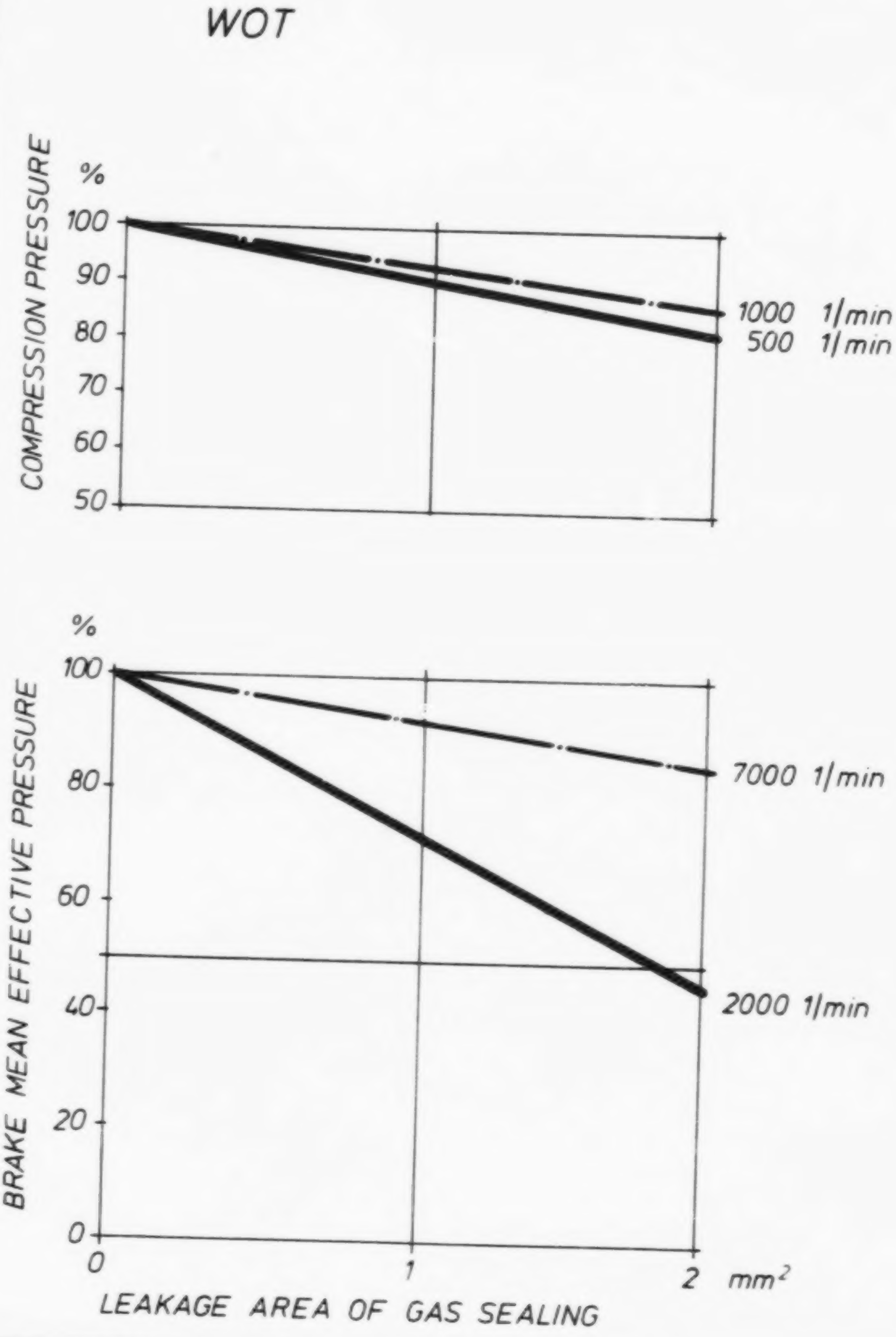
INFLUENCE OF GAS SEALING
LEAKAGE AREA ON SFC

Fig. 4



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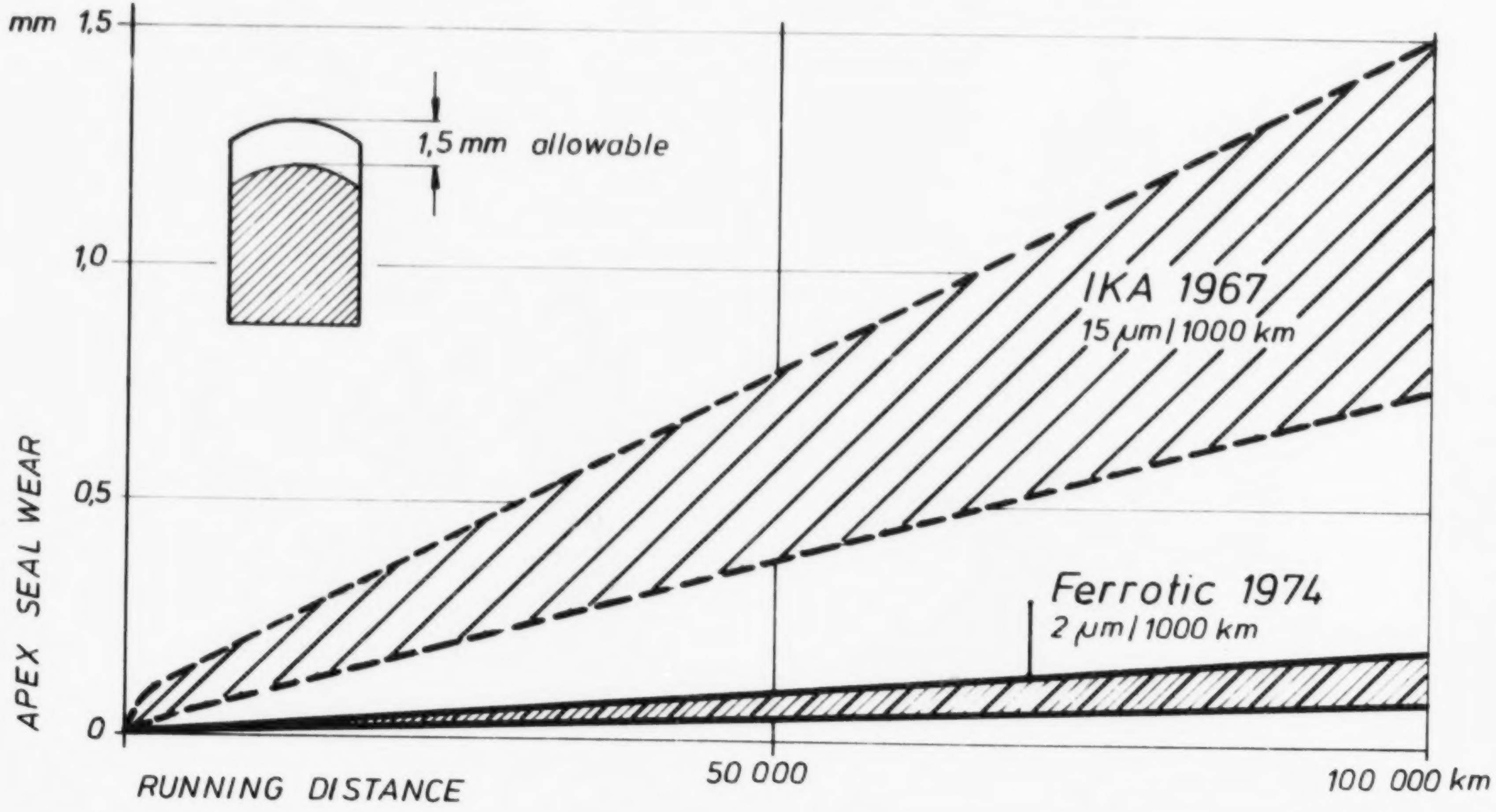
INFLUENCE OF GAS SEALING
LEAKAGE AREA ON BMEP AND
COMPRESSION PRESSURE

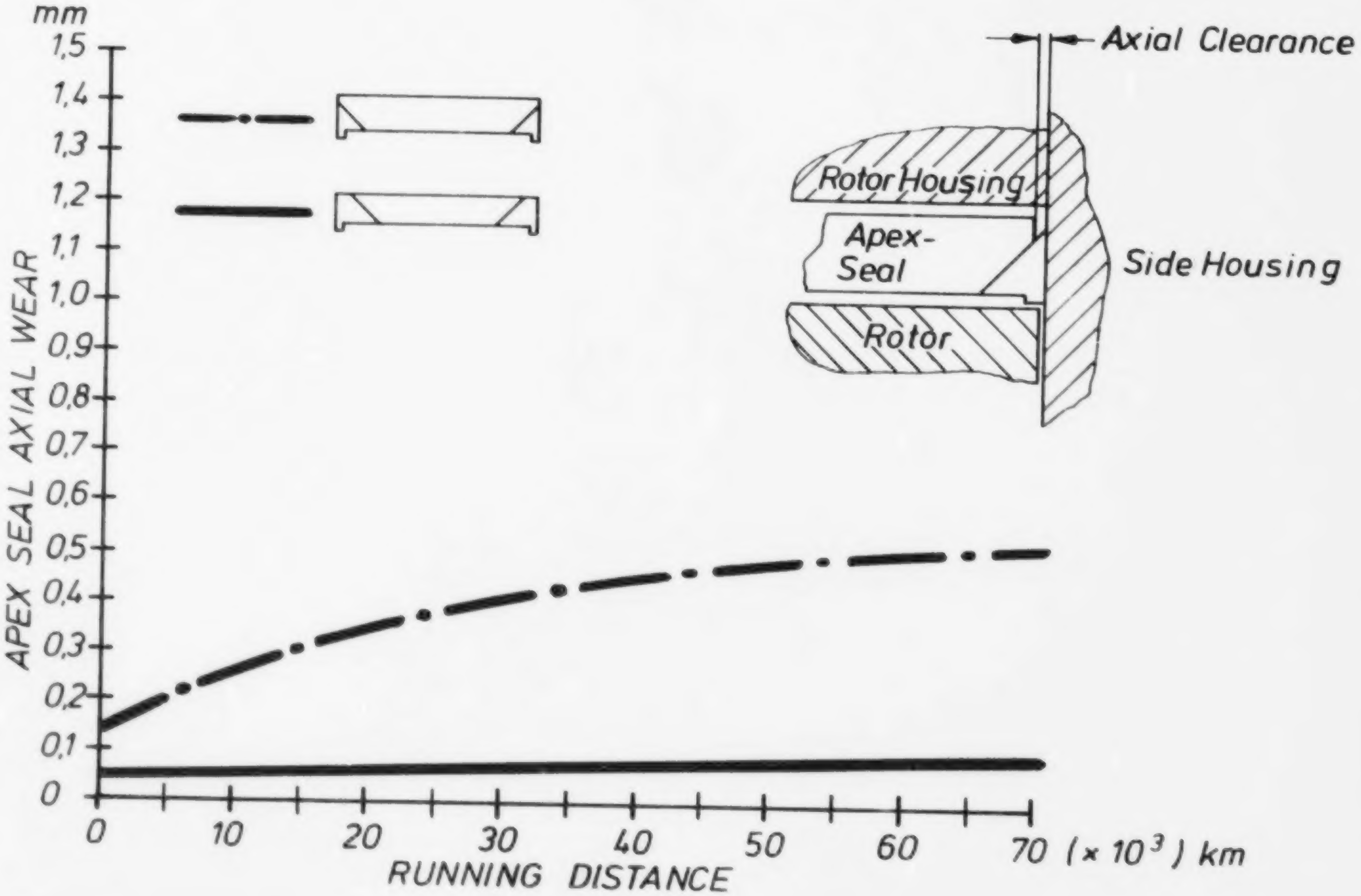
Fig. 5



AUDI NSU

APEX SEAL WEAR AT ROAD TEST

Fig. 6



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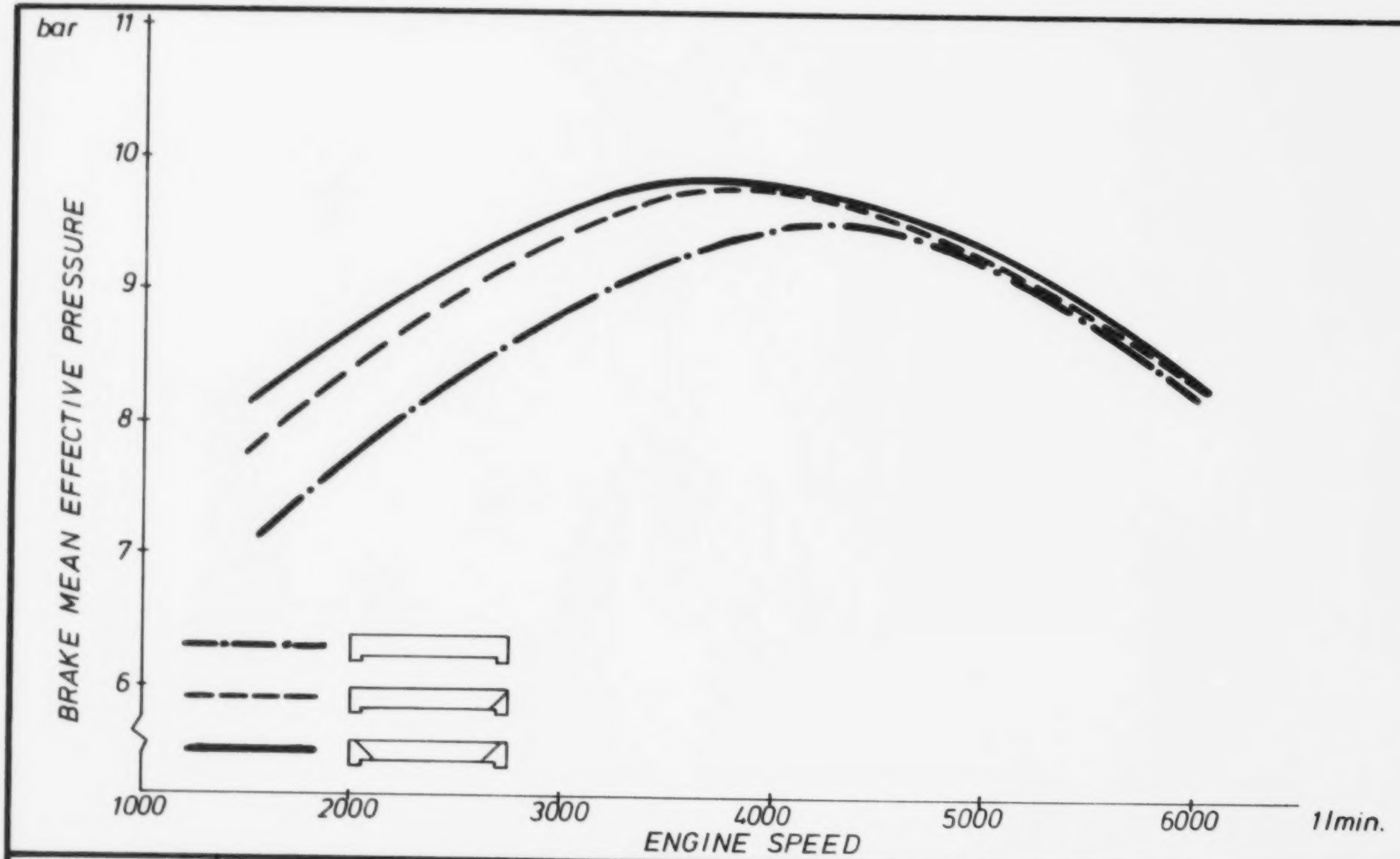
AVERAGE AXIAL APEX SEAL WEAR

Fig. 7



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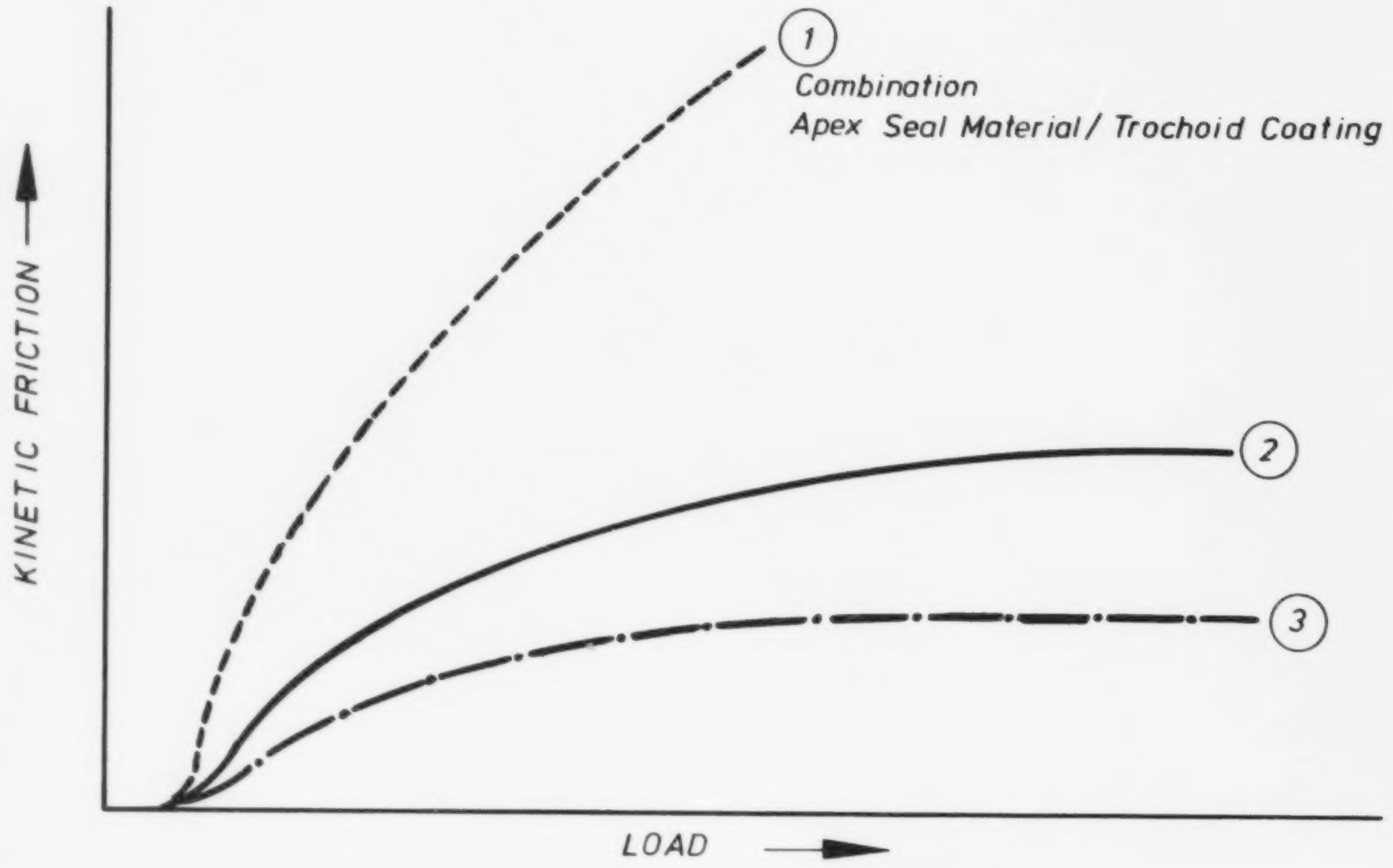
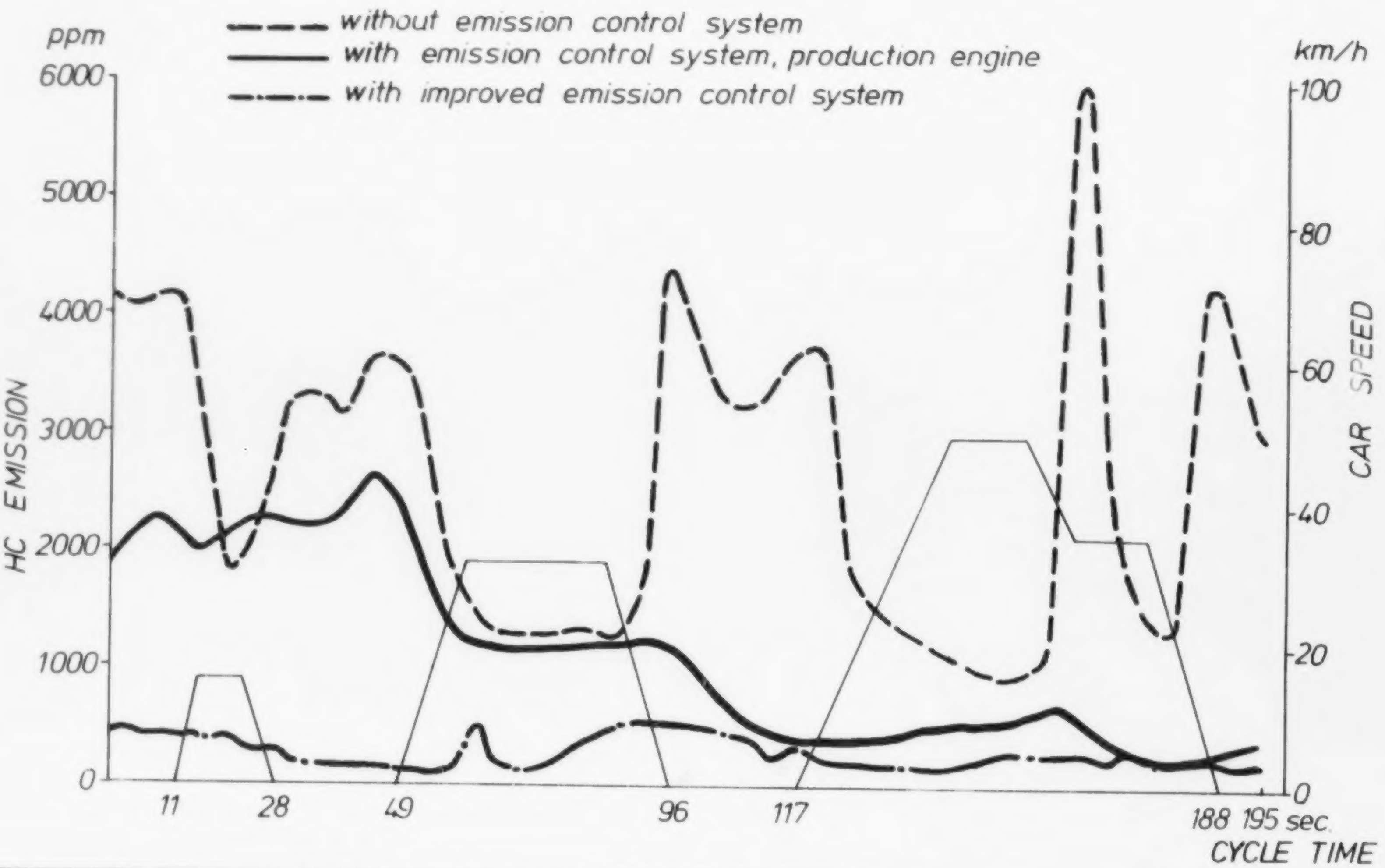
COMPARISON OF 1-, 2-, 3-
PIECE APEX SEAL ON BMEP AT W.O.T

Fig. 8



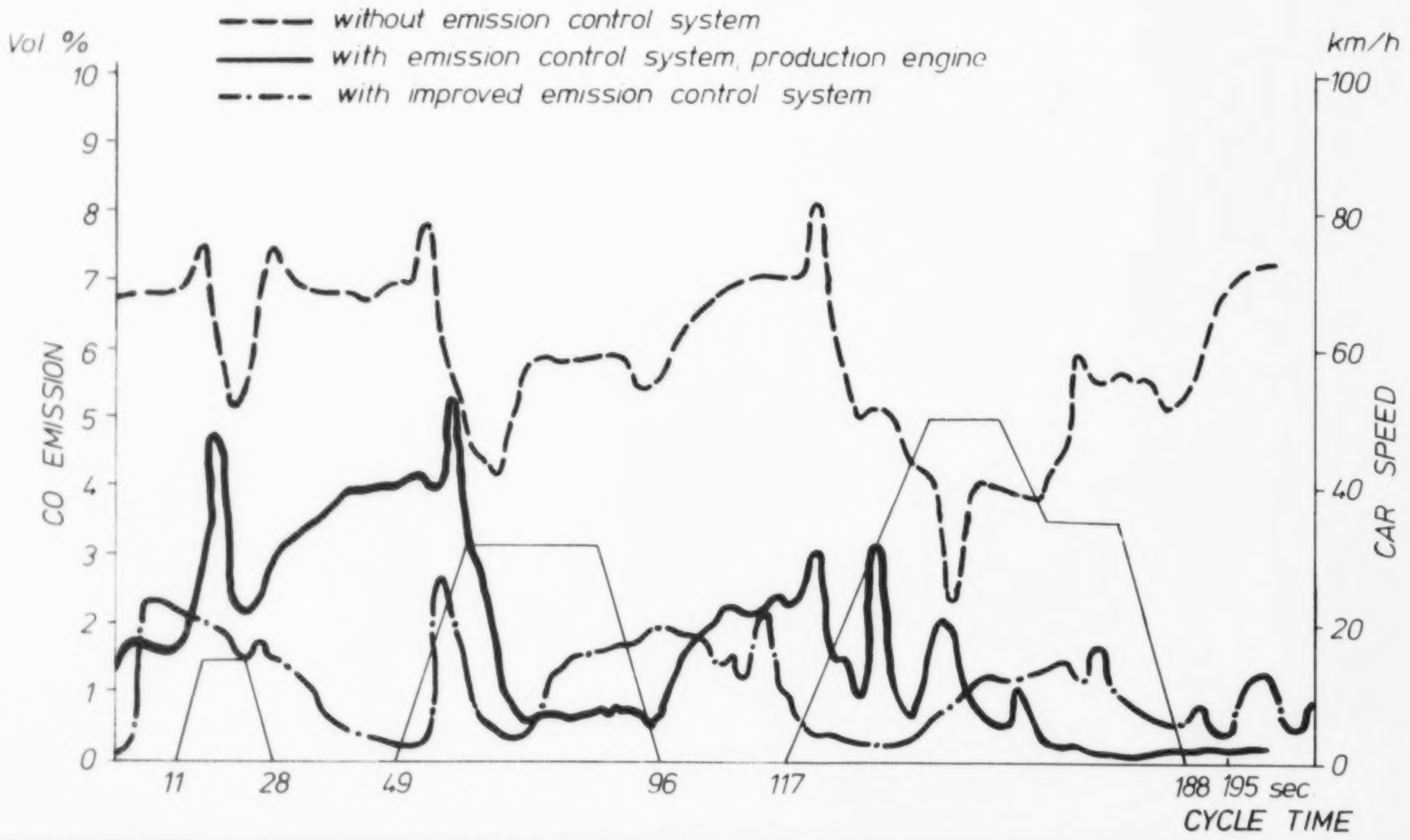
AUDI NSU | FRICTION TEST OF VARIOUS WEAR COMBINATIONS | Fig. 9



AUDI NSU

HC EMISSION IMPROVEMENT
IN EUROPEAN TEST CYCLE No. 1

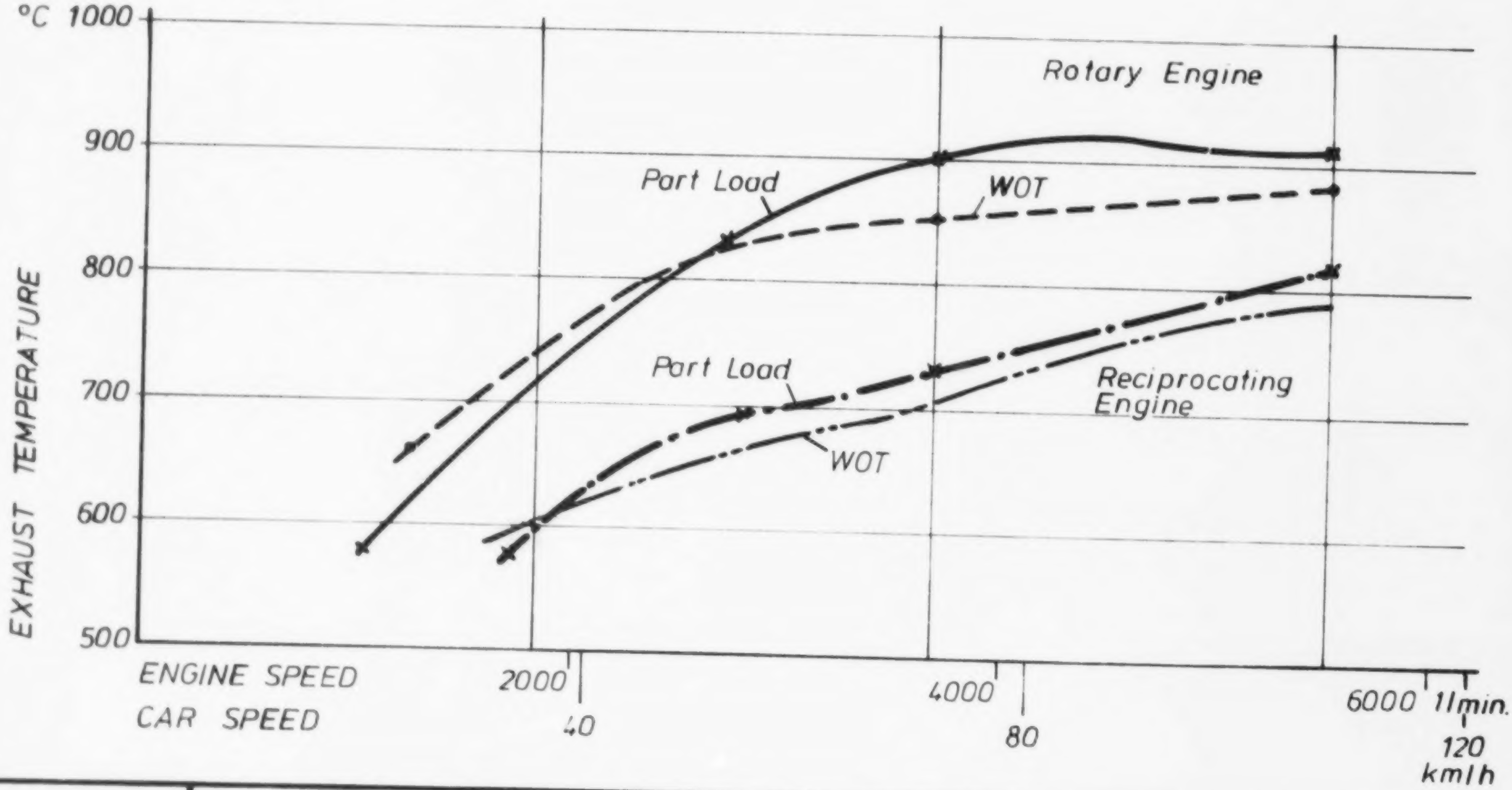
Fig. 10



AUDI NSU

CO EMISSION IMPROVEMENT
IN EUROPEAN TEST CYCLE No. 1

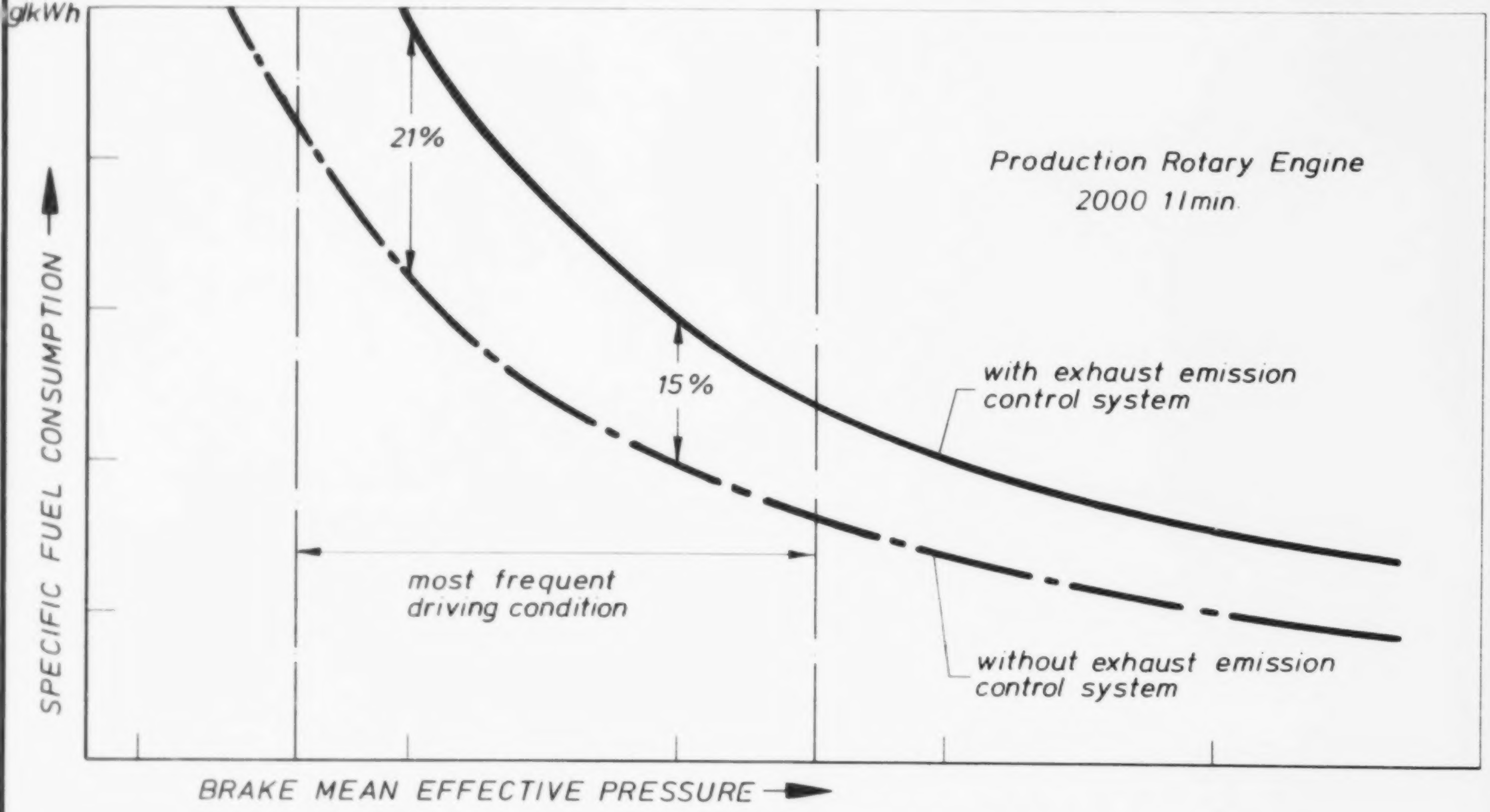
Fig. 11



AUDI NSU

EXHAUST GAS TEMPERATURE

Fig. 12



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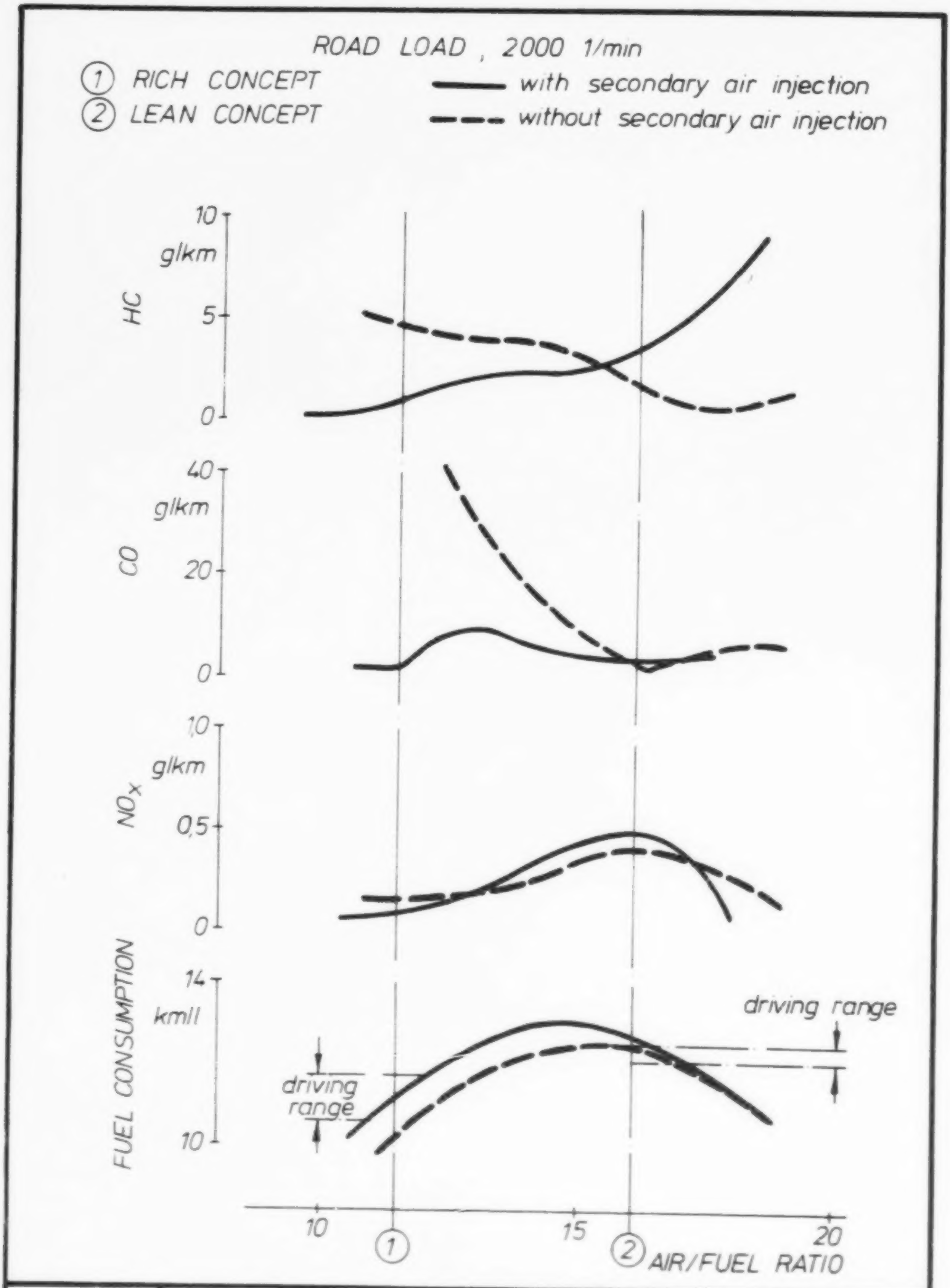
SPECIFIC FUEL CONSUMPTION WITH AND WITHOUT EXHAUST EMISSION CONTROL SYSTEM

Fig. 13



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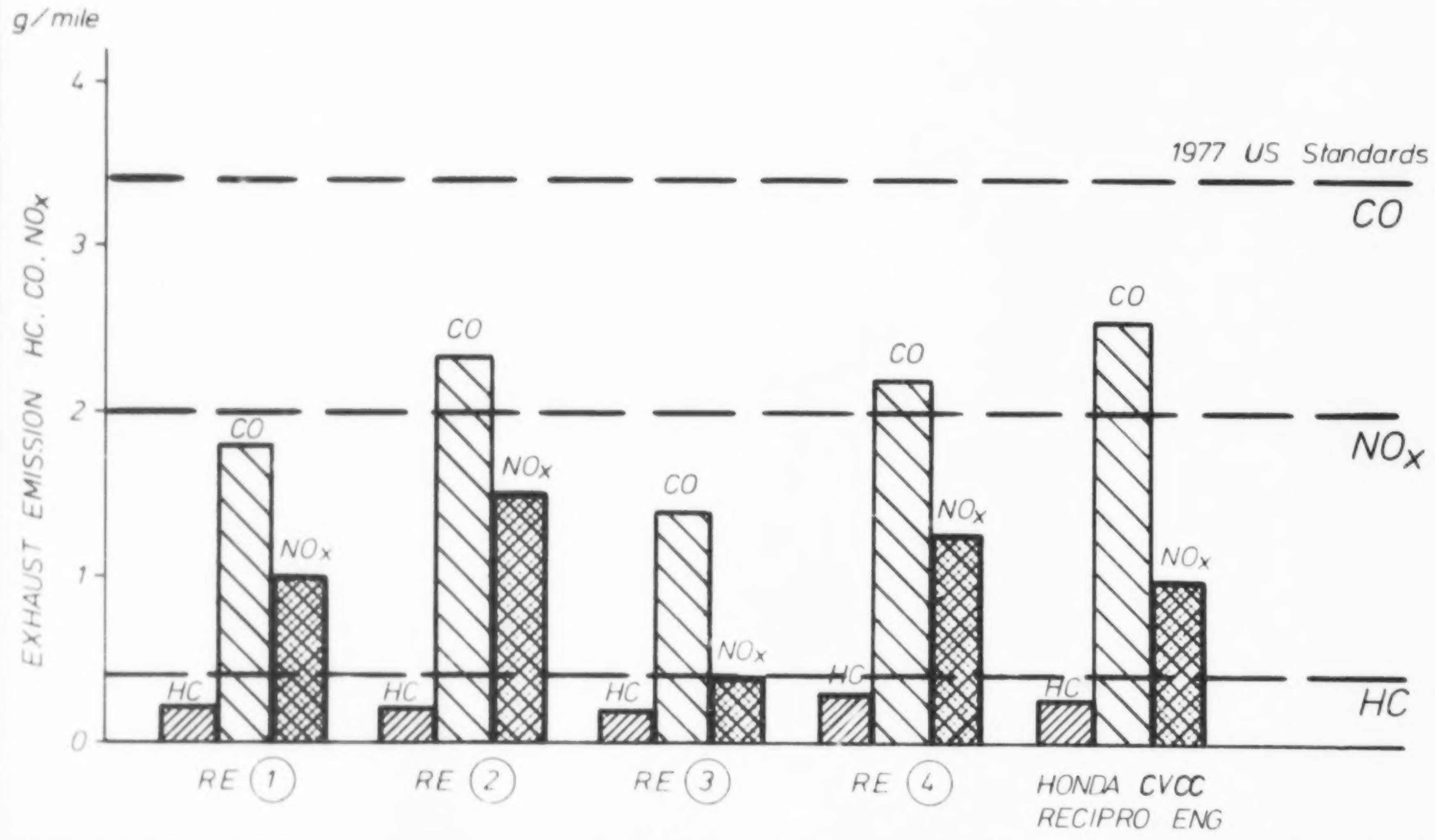
EXH. EMISSION AND FUEL CONSUMPTION OF RICH AND LEAN CONCEPTS WITH THERM. REACTOR

Fig. 14



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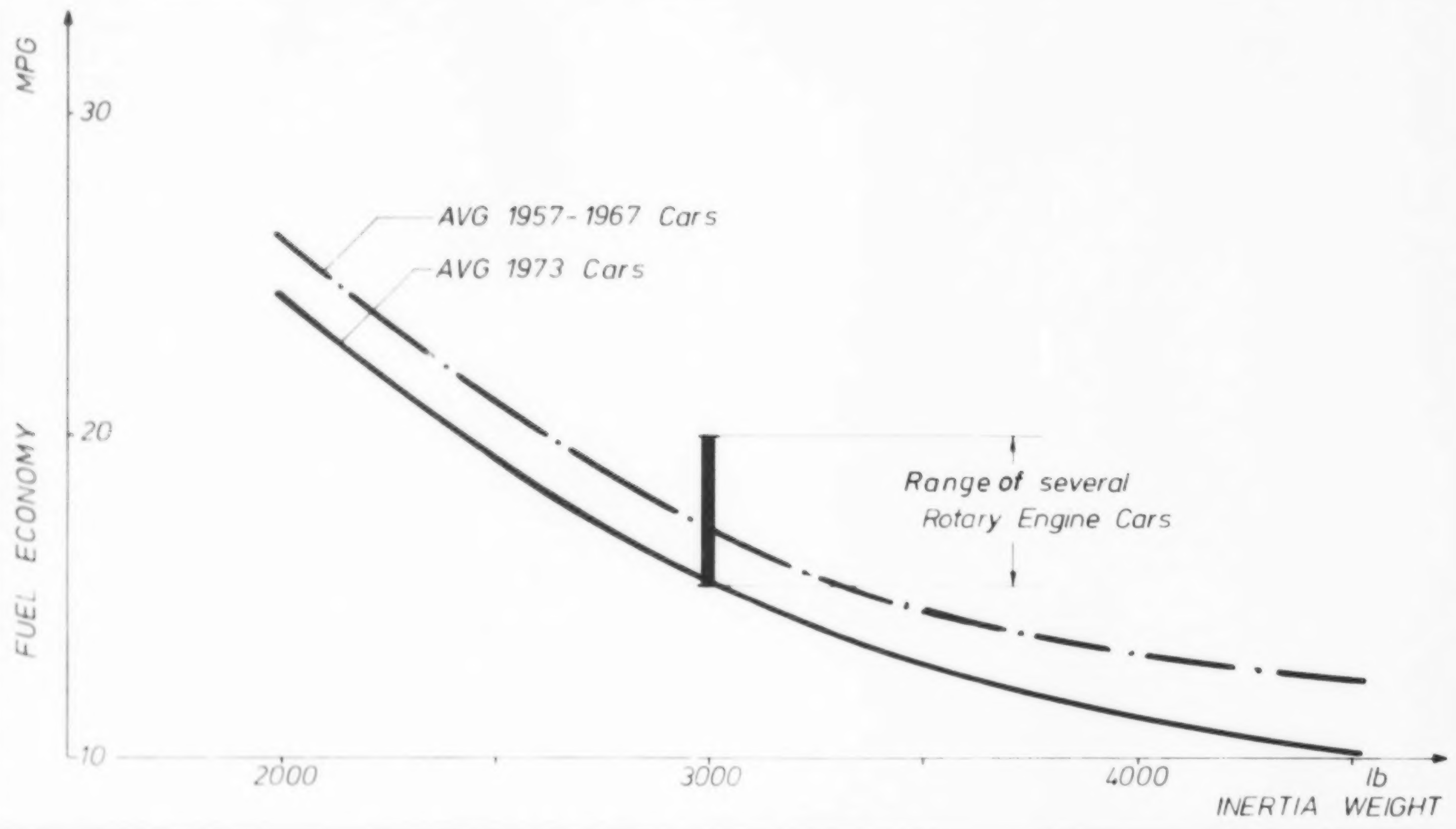
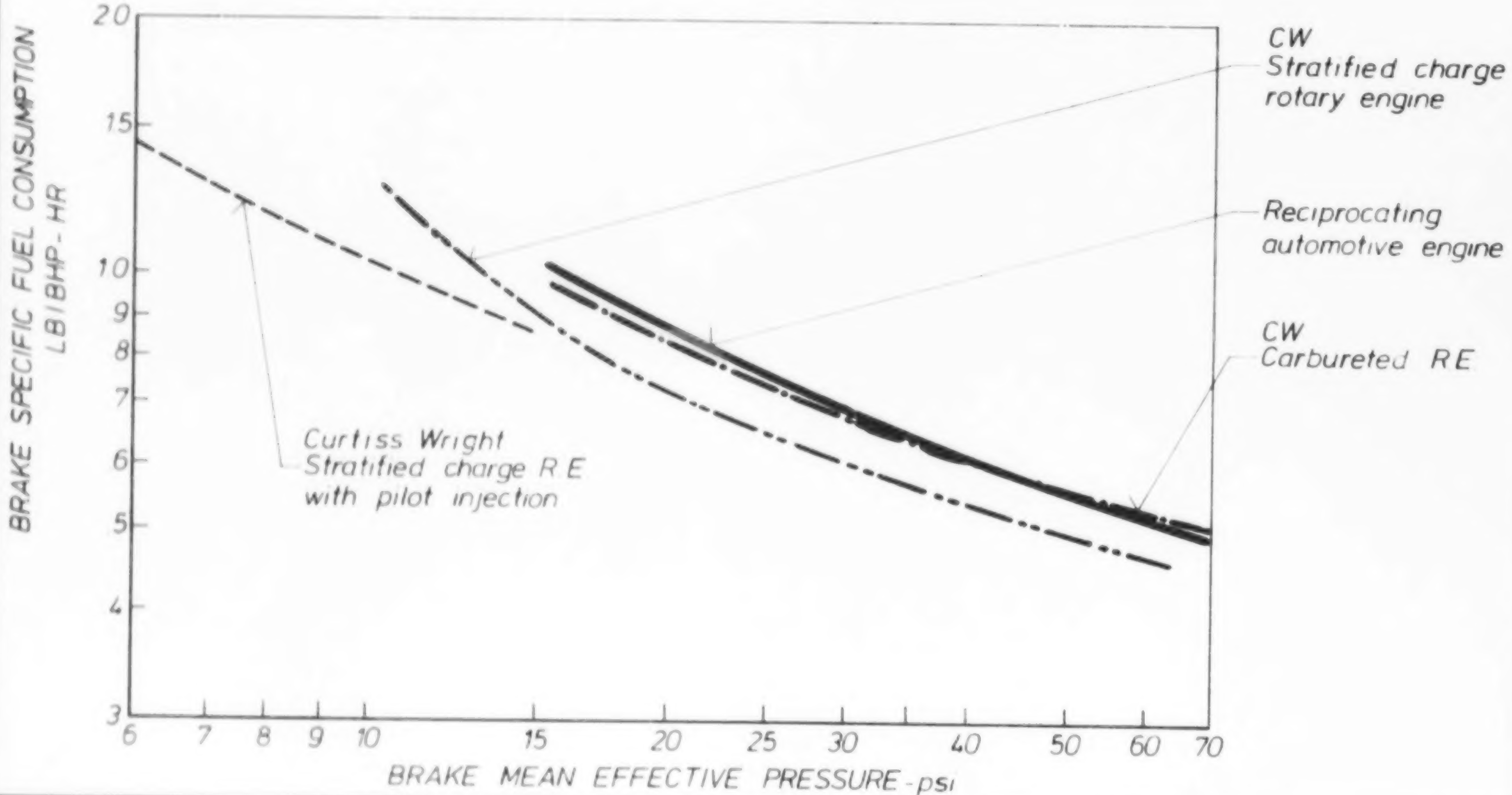
HC, CO, NO_x EMISSIONS WITH DIFFERENT R.E. AND EMISSION CONTROL SYSTEMS

Fig. 15



AUDI NSU | FUEL ECONOMY OVER THE FEDERAL DRIVING CYCLE | Fig. 16



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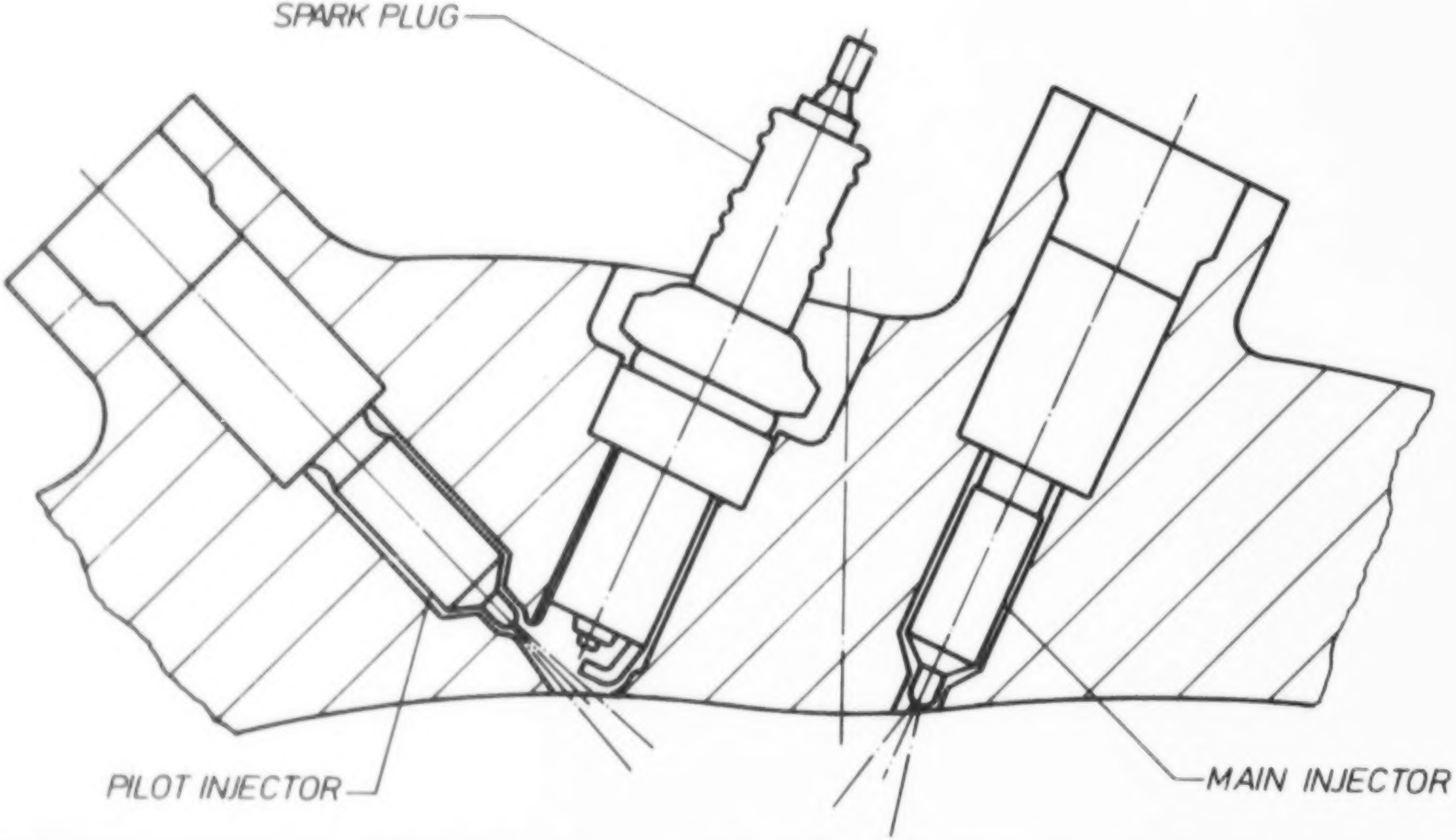
PART LOAD FUEL CONSUMPTION, 2000 1/min.

Fig. 17



AUDI NSU

C.W. STRATIFIED CHARGE ENGINE
PILOT LIGHTED DUAL INJECTOR CONFIGURATION

Fig. 18

Low Pollutant Combustor Development as Part of Volkswagens Passenger Car Gas Turbine Research Program *)

R. BUCHHEIM and P. WALZER
Research Division, Volkswagenwerk AG, Wolfsburg, Germany

One important part of Volkswagens gas turbine research program is the development of a low pollutant and multifuel combustion system. Preliminary results of this government sponsored research program are presented. A procedure to predict the nonsteady state operating range of the important combustion system variables is described. For various burner types the emission characteristics were experimentally determined

Un objectif important du programme de recherches effectué par la Volkswagenwerk sur les turbines à gaz est la mise au point d'un système de combustion dégageant peu de polluants et permettant l'utilisation de combustibles divers. Les premiers résultats de ce programme de recherches soutenus par l'Etat sont communiqués. Est exposé un procédé de prévision du domaine de fonctionnement non stationnaire des paramètres les plus importants du système de combustion. Le comportement au point de vue des émissions des différents types de chambres de combustion est déterminé expérimentalement.

Ein Schwerpunkt des Gasturbinen-Forschungsprogramms der Volkswagenwerk AG ist die Entwicklung eines schadstoffarmen und vielstoffähigen Verbrennungssystems. Erste Ergebnisse dieses staatlich geförderten Forschungsprogramms werden mitgeteilt. Ein Verfahren zur Vorhersage des instationären Betriebsbereichs der wichtigsten Einflußgrößen des Verbrennungssystems wird erläutert. Das Emissionsverhalten verschiedener Brennkammerarten wird experimentell bestimmt.

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*) Sponsored by the Federal Minister for Research and Technology

1. Introduction

Besides the continuing effort to improve the conventional engines, the Volkswagenwerk AG is investigating the possible operation of unconventional engines. One such engine is the gas turbine. The interest in this engine lies principally in its low pollutant capability and, what might also be of importance in the future, in its capability to use a wide variety of fuels.

For the purpose of gathering knowledge and developing experience with gas turbines, an experimental engine was built and tested. This engine, a 75 HP passenger car gas turbine, has been described at the last CCMS meeting and in some other publications [1], [2], [3]. A VW microbus powered by this engine can be seen in the exhibition area of this meeting.

The results of this first phase showed such clear advantages for low pollutions that further investigations with this type of engine were justified. It also showed the main problems, namely part load fuel consumption, NO_x-emissions, and production costs, which must be solved before mass production of a passenger car equipped with a gas turbine engine can be realistically considered.

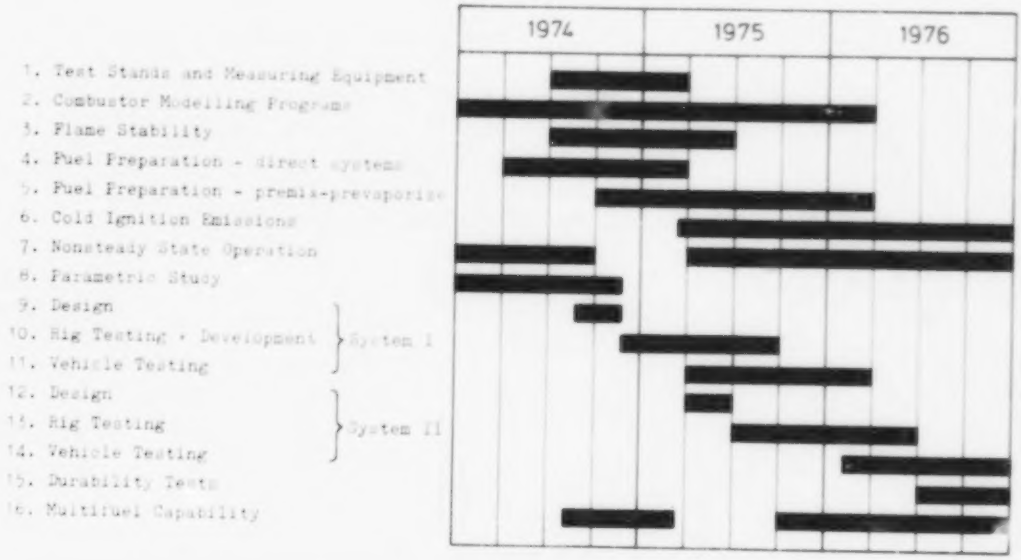
Our present work is therefore concentrated on improving those items. Our efforts in applications of high temperature ceramics, which offer the possibility of improved fuel consumption and lower production costs, and our efforts on a low emission and multifuel combustion system are being partially sponsored by the Deutsche Bundesministerium für Forschung und Technologie.

A report on our ceramic program will be given at one of the next CCMS meetings. Our program entitled "Development of a Low Emission and Multifuel Combustion System for Passenger Car Gas Turbines" is a 3 year program which we started in January 1974. As engine parameters, which influence design and operation of this combustion system, we assume a regenerative gas turbine, which should be able to power a 1400 kg vehicle in a typical passenger car driving cycle with performance and fuel consumption comparable to that of an Otto engine but with lower emissions.

The schedule and first results of this program will now be presented by Mr. Buchheim.

2. Combustion System Development Program

Figure 1 shows the time schedule and the main activities of the combustion system development program.



Combustion System Development Schedule

Fig. 1

The final goal of the program is to demonstrate 2 systems in a gas turbine equipped passenger car. System I will be a low cost modified conventional system with fixed geometry. System II will be a premix,prevaporizing system which will incorporate devices for maintaining the fuel-air ratio in the combustion zone within a narrow range. System II should, especially for NO_x, give lower emissions but will be more complex than System I.

From Volkswagen's earlier experience with the VW-GT 70,the main problem areas for a low emission, multifuel combustion system are the following:

a. For the design of a low pollutant combustion system the nonsteady state operating range of the variables important for emissions has to be known precisely.

3

b. Compared with the emission legislation in effect or proposed in various countries, the NO_x-emissions of present day systems are too high at all operating states. To solve this problem new design features have to be adopted.

c. The CO- and HC-emissions are only a problem at nonsteady state operation, especially at deceleration. Here the control mode for deceleration and braking has to be chosen not only according to drivability and fuel consumption but also according to best emission performance.

d. The CO and especially the HC-emissions at cold ignition are a serious problem. To solve this problem, considerable development in the test rig and in the engine will be necessary.

e. Multifuel capability with low emissions will be mainly a problem of control system and fuel preparation system design. The combustion chamber itself can be used unchanged for various fuels.

As Figure 1 shows, activities will be concentrated on these problem areas. According to the time schedule the nonsteady state operating characteristics (item 7 in Figure 1) important for emissions of the gas turbine will be investigated before we design System I. In addition, a parametric study (item 8 in Figure 1) on our burner test stand will serve as a basis for the combustor designs.

In the following a short summary of the main results so far obtained in these studies will be given.

3. Volkswagen Combustion Test Stand

Before the program started in January 1974, Volkswagen built a test stand which allows complete simulation of regenerative passenger car gas turbine combustion systems.

In Figure 2 a photograph of the test stand is shown. The important features of the test stand are: regenerative preheating, independent variation of the main combustion parameters, and automatic data acquisition. A test rig was designed to simulate the flow conditions in a regenerative gas turbine. Provisions for special measurements such as combustion zone probing, pressure, temperature and flow destributions at various positions are incorporated in the rig. The rig also allows adaptions for various shapes and sizes of combustors.

VW Burner Test Stand | Fig. 2

4. Nonsteady State Operation Characteristics of a Regenerative Gas Turbine Combustion System

Presently the emission legislation in the U.S. has the strongest requirements. Therefore the US-Federal Driving Cycle (F.D.C.) is chosen for the evaluation of nonsteady state operation characteristics of a combustion system for a passenger car gas turbine.

4.1. Analogue Computer Model

For detailed nonsteady state evaluation an analogue computer model for a regenerative gas turbine was constructed. The behaviour of this turbine together with a 1400 kg vehicle during the F.D.C. was investigated.

With this model studies were performed to reveal the following features.

a. Best modes of control system operation for low emissions, best fuel consumption,and good drivability during the F.D.C.

b. Nonsteady state operating range of the variables important for low emissions during the F.D.C.

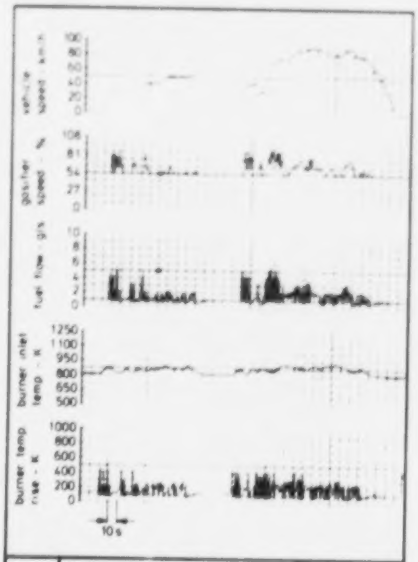
c. Analysis of the emission contributions of various modes during the F.D.C.

d. Steady state conditions suitable for simulating the nonsteady state F.D.C. on the combustor rig.

First the optimum control system requirements were established using the analogue model. All the following investigations with the analogue model were performed with the optimum control system requirements resulting from this study.

4.2. Operating Range of Variables During the F.D.C.

To establish the operating range and the histograms of the important engine parameters during the F.D.C., the analogue model was used.

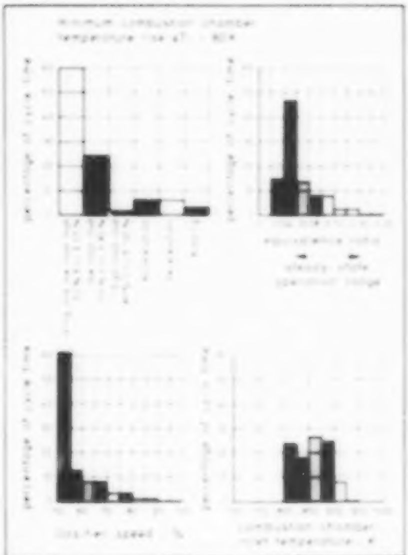


History of Operating Parameters during the F D C from Analog Computer Simulation

Fig 3

Figure 3 shows the behaviour of some important variables during the first 300 seconds of the F.D.C. Notice that the fuel flow and the combustion chamber temperature rise show sharp peaks during gas generator acceleration whereas the combustion chamber inlet temperature has a smoother behavior. This behavior is caused by the ability of the regenerators to act as a short term heat source or sink.

Figure 4 shows the histograms of some operating parameters during the F.D.C. The most important conclusion to be made from this figure is that for a significant amount of the time during the F.D.C. the combustion system operates at air-fuel ratios below that of stationary idle. This results from the transient storage of heat in the regenerators.



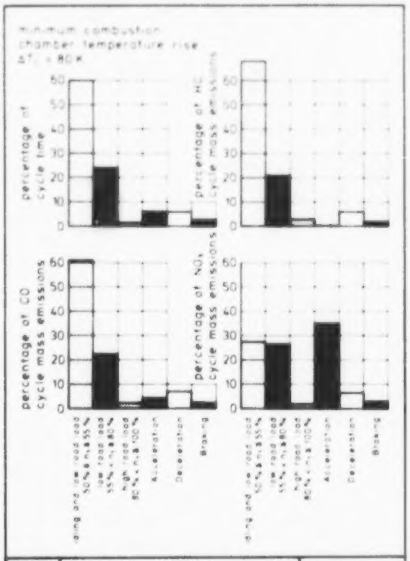
Histograms of Operating Parameters

Fig 4

Furthermore, gas generator speeds greater than 80 % are reached less than 2 % of the time, but the corresponding stationary equivalence ratio of 0.15 is exceeded 6 % of the time. This occurs mainly during acceleration.

4.3. Analysis of Emissions during the F.D.C.

To reveal the deficiencies with respect to emission performance of a particular combustion system and in order to adjust the design parameters in the proper way, it is important to get information about when during the F.D.C. the emissions are produced. Experimental curves showing the steady state emission performance of the combustor as a function of combustor inlet temperature and combustor temperature rise were used together with the analogue computer model of the gas turbine to generate the desired data. Results for a lean primary zone combustor are given in Figure 5.

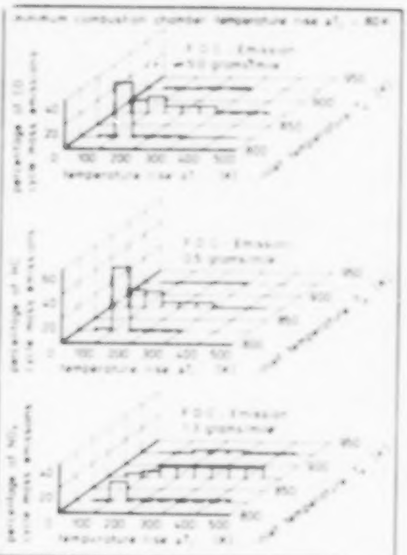


Modal Emission Contributions during the F.D.C.

Fig 5

Figure 5 shows that more than 60 % of the CO- and HC-emissions occur during idling. Thus, a reduction in the pollutants from the investigated combustor in this operating range alone would greatly improve the overall emission levels. On the other hand, most of the NO_x is produced during acceleration; idling and low road load also contribute significant amounts of NO_x. For NO_x therefore a reduction over the entire operating range is required.

Figure 6 shows the emission contributions as a function of various combustor inlet temperatures and temperature rises. Here it is obvious that most of the CO and HC is generated at inlet temperatures between 800 and 850 K and temperature rises between 100 and 150 K. However significant amounts of NO_x are generated over a wide range of inlet temperatures and temperature rises.



Emission contributions of various inlet temperatures and temperature rises during the F.D.C.

Fig 6

4.4. Simulation Data for Rig Testing

In order to get data about the emission performance of the tested combustion system under F.D.C. conditions from stationary combustor rig testing, the analogue model was used to calculate histograms for the F.D.C.These histograms show the percentage of time and the percentage of total cycle fuel consumption for several ranges of inlet temperatures and temperature rises. By combining the data from these histograms and by using the total cycle fuel consumption, the F.D.C. emission performance can be calculated from the emission performance at the 9 stationary points shown in Table 1.

Point - Nr		1	2	3	4	5	6	7	8	9
burner inlet temperature	K	925	875	875	875	875	825	825	825	825
pressure	bar	1.8	2.0	1.8	1.7	2.2	3.3	1.8	1.7	2.1
fuel flow	kg/h	6.74	2.34	3.55	5.89	12.44	4.37	3.44	5.37	13.37
air flow	kg/s	0.30	0.29	0.28	0.26	0.32	0.53	0.27	0.24	0.34
fuel consumption m_i	grams	103	103	155	448	190	17	551	103	52

The emission E_{FDC} in g/mile during the FDC is $E_{FDC} = \frac{\sum EI_i \, m_i}{7.5}$

Data Points for FDC Simulation on Burner Test Rig

Table 1

5. Parametric Studies

Significant NO_x-production can be suppressed in either a very lean or in a rich combustion zone.

Based on available combustor design criteria and with the help of NO_x and CO combustor modelling computer programs, rich (burner Type R) and lean (burner Type L) reaction zone combustors were designed.

5.1. Design Considerations

In designing a burner with a rich reaction zone, the following points were observed:

a. The combustion products from the rich reaction zone have to be diluted very rapidly in an intermediate zone to temperatures for which the NO_x-kinetics are slow. Otherwise significant amounts of NO_x will be formed in the rich-lean transition region with equivalence ratios around stoichiometric.

b. The combustion products of a rich reaction zone contain significant amounts of CO and partially burned hydrocarbons. Therefore after the reaction zone the diluted gases must have enough residence time at temperatures where CO- and HC-oxidation still can proceed. This can be done in a rather voluminous secondary zone added behind the rapid-quench intermediate zone.

c. The problem of wall cooling in a rich reaction zone has to be solved. Combined film and convective cooling can be used.

For the lean reaction zone burner the following points were observed:

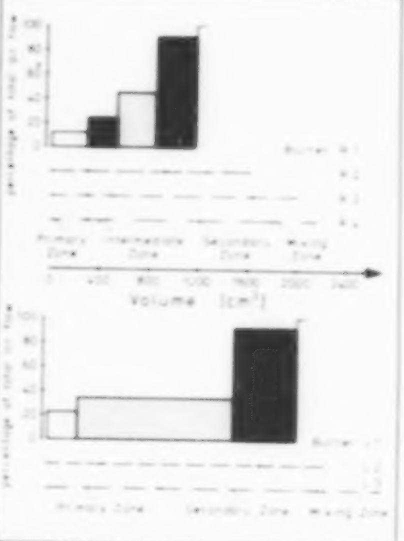
a. A secondary zone for CO- and HC-oxidation at higher loads is necessary.

b. Flame stability determines the lean end of the operating range. Strong recirculation, induced through the incorporation of radial swirlers, and increased combustion zone volume were provided.

c. To get low NO_x-values good mixing with a lean burner is very important.

In the R-type burner, residence times and mixing characteristics in the intermediate and secondary zone are important for performance and emissions. Therefore based on predictions of combustor modelling programs, R-type burners with different residence times in these zones were designed. The primary zone volume was kept constant.

For the L-type burners volume and mixing characteristics of the primary zone are important. Therefore the L-type burners were designed with different primary zones.



Air Flow and Zone Volumes for Burners Used in Volumetric Study

Fig 7

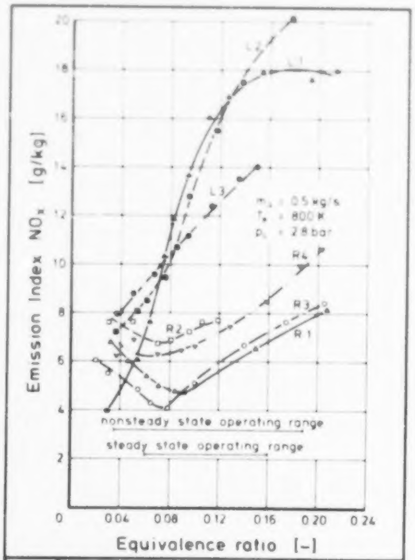
In Figure 7 the mean calculated air flow into the zones and the zone volumes of the various combustors which were experimentally investigated are shown.

5.2. Experimental Results

Figures 8 - 10 show the emissions of the investigated burners tested with an air assist fuel injection system.

When the various burners are compared, quite a different behavior of the pollutant emissions over the investigated range of equivalence ratios for the R- and L-type burners is observed.

The NO_x-emissions are shown in Figure 8. All the rich reaction zone (type R) burners show a minimum at an equivalence ratio between 0.06 and 0.10. At smaller and higher equivalence ratios the NO_x-emission increases slightly. In the nonsteady state operating range, the ratio between maximum and minimum NO_x-emission for all R-type burners is less than 2.



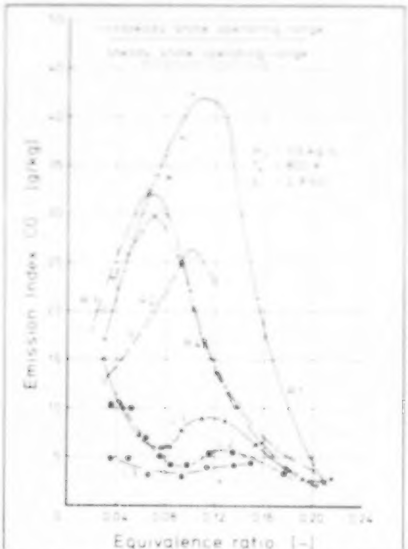
NO_x-Emissions of Experimental Burners

Fig 8

All the L-type burners show a steep increase of NO_x-emissions with equivalence ratios. In the operating range the ratio between maximum and minimum NO_x-emission is greater than 4.

The influence of zone volumes on NO_x-emissions basically shows that for the R-type burners at low equivalenne ratios the intermediate zone is predominant whereas at high equivalence ratios some NO_x is formed even in the secondary zone. The lean burners show at low equivalence ratios the expected higher NO_x-values for longer primary zone residence times. This is no longer true above an equivalence ratio of 0.06. Here the largest volume primary zone burner, L3,has the lowest NO_x-levels. Since the result cannot be explained by residence time changes it is attributed to possible changes in the mixing and recirculation pattern.

The CO-emissions are shown in Figure 9. Clearly the lean burners give much lower CO-emissions than the rich burners. In addition the R-type burners show a pronounced maximum at equivalence ratios between 0.06 and 0.10, whereas the lean burners show a significant increase in CO at the lean end of the operating range. In this case these burners are operating close to the lean stability limit. On the other hand the rich burners are at the lean end of the operating range, not near their stability limit.



CO-Emissions of Experimental Burners

Fig 9

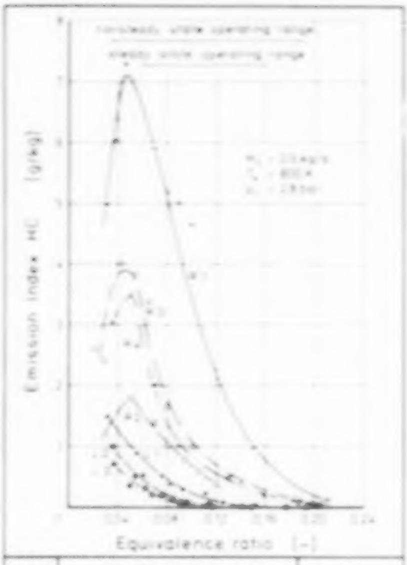
The influence of zone volumes on CO can be analyzed as follows: The rich burners show that at high equivalence ratios the residence time in the secondary zone has a pronounced influence on CO. For larger reaction zone volumes the lean burners give the expected better stability characteristics at the lean end.

The HC-emissions shown in Figure 10 reveal a behavior similar to the CO-values.

In Table 2 the results are given for the F.D.C. simulation on our combustor test rig. All the R-type burners have NO_x-values below 2 grams/mile, the present US-77 limit. Only the R2 burner meets the

US-77 limits for all 3 pollutants.

The lean burners have all CO and HC-values far below the US-77 limits; the NO_x-values are all between 2-3 gr/mile.



HC-Emissions of Experimental Burners

Fig. 10

6. Summary

We have established a procedure to predict the nonsteady state operating range of the important combustion system variables. For various burner types the emission characteristics over the operating range were experimentally determined.

These results together with the results we expect from our studies which are performed under points 2, 3, and 4 in Figure 1 will serve us as a basis for the design of system I.

Burner type	NO_x	CO	HC
	g/mile	g/mile	g/mile
R 1	1.3	6.5	0.9
R 2	1.8	2.9	0.2
R 3	1.4	3.5	0.3
R 4	1.7	3.5	0.3
L 1	2.1	1.4	< 0.2
L 2	2.4	0.9	< 0.2
L 3	2.1	0.8	< 0.1

Results of Combustor Rig F.D.C. Simulation

Table 2

7. Literature

[1] P. Walzer, P. Rottenkolber, G. Hagemann: Die VW-GT 70 eine Versuchsgasturbine für den Pkw-Antrieb. MTZ 34, Nr. 9, 1973.

[2] P. Walzer, R. Buchheim, P. Rottenkolber, G. Hagemann: Passenger Car Performance with the Experimental Gas Turbine VW-GT 70. ASME 74-GT-108 1974.

[3] R. Buchheim: Das Emissionsverhalten der Personenwagen-Gasturbine VW-GT 70. MTZ 35, Nr. 3, 1974.

REPORT OF THE EPA/AAPSD* - CHRYSLER CORPORATION GAS TURBINE DEVELOPMENT PROGRAM

*EPA - Environmental Protection Agency
AAPSD - Alternative Automotive Power System Division

Sebestyen, Thomas M., EPA/AAPSD, USA

Wagner, Charles E., Chrysler Corporation, USA

Lewis, Leon D., Garrett/AiResearch, USA

This paper is a review of:

1. The overall status of the EPA/AAPSD gas turbine activity, and the specifications and rationale for the Upgraded Engine burner.
2. The general status of Chrysler Corporation Baseline Gas Turbine Development Program including a description of the approaches and progress towards achieving Upgraded Engine fuel economy and emissions goals.
3. Progress to date by Garrett/AiResearch on the design and development of an integrated control system for the Upgraded Engine.

INTRODUCTION

By T. M. Sebestyen

EPA/AAPSD

EPA/AAPSD GAS TURBINE PROGRAM UPDATE

Since the last LPPSD Meeting in October of 1973 and even since the last EPA/AAPS Division Contractors' Coordination Meeting in May of 1974, significant events have taken place in our program to develop and evaluate the gas turbine as a low pollution powerplant for future automobiles.

Most of the progress in the program is associated with the Chrysler project. Those will be described in detail in the next two sections of our report.

Overall, the direction of the program has changed somewhat as the pendulum of emphasis has swung some more between emissions and fuel economy as in the preceding years (Figure 1). In response to the changes in global priorities, our program has officially adopted the "compact" car as the vehicle with which emissions and improved fuel economy will be demonstrated.

EPA/AAPSD GAS TURBINE PROGRAM

RELATIVE EMPHASIS BETWEEN

EMISSIONS AND FUEL ECONOMY

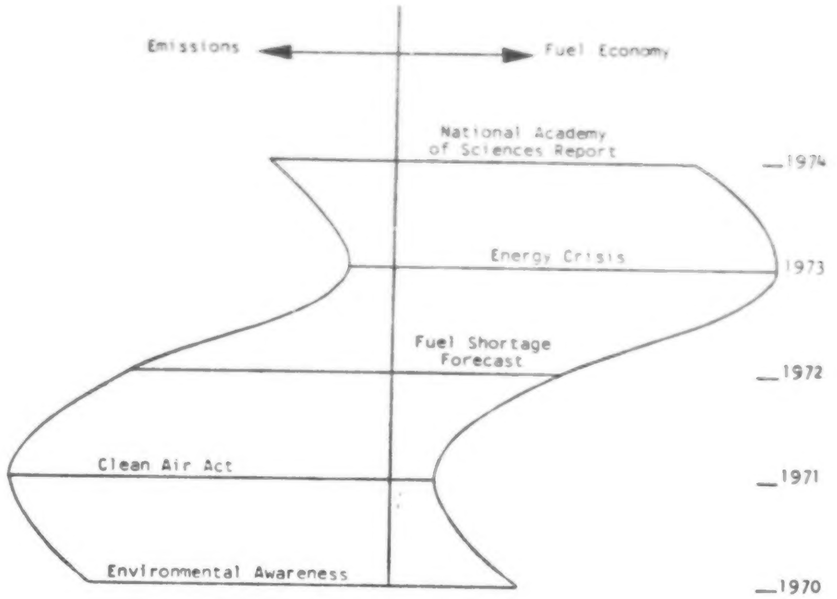


Figure 1

In addition, preliminary planning has commenced on longer range and higher "yield" programs that would simultaneously answer the demands of ecology, conservation of resources and economics. The establishment of an Energy Research and Development Agency (ERDA) in the United States is expected in the near future, under the authority of which these efforts would be undertaken. New elements in the gas turbine program have been directed to facilitate the start of these activities. The program team is now expanding, and future expansion is possible in the directions indicated in Figure 2.

Particularly significant in this expansion is the emphasis on ceramics. Accordingly, our Division has arranged for the presentation of two related papers from Ford Motor Company and one from the Army Mechanics and Materials Research Center at this symposium.

It is expected that when ERDA is established, increased funding will be available for ceramic technology, an area not now funded at a level commensurate with its potential for the future (Figure 3). The questionmark signifies the fact that until Congress votes ERDA into being, associated funding will be in limbo.

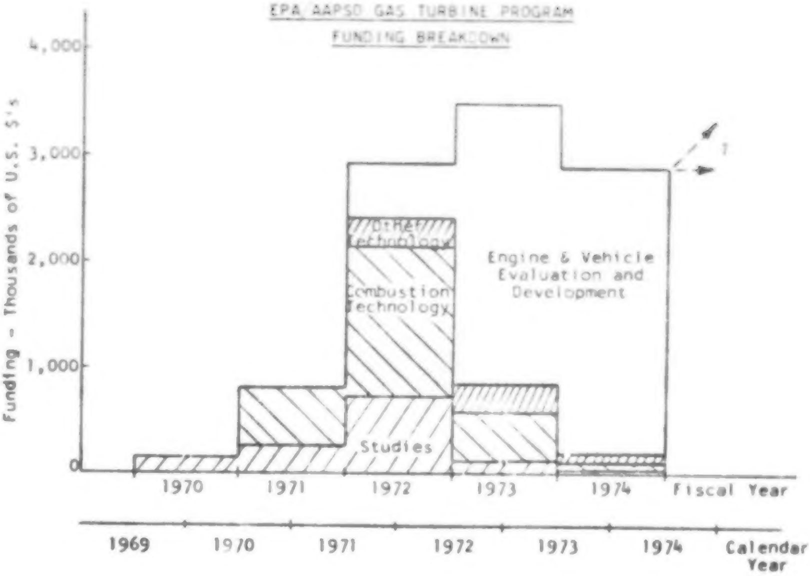


Figure 3

EPA/AAPSD GAS TURBINE PROGRAM TEAM (1974)

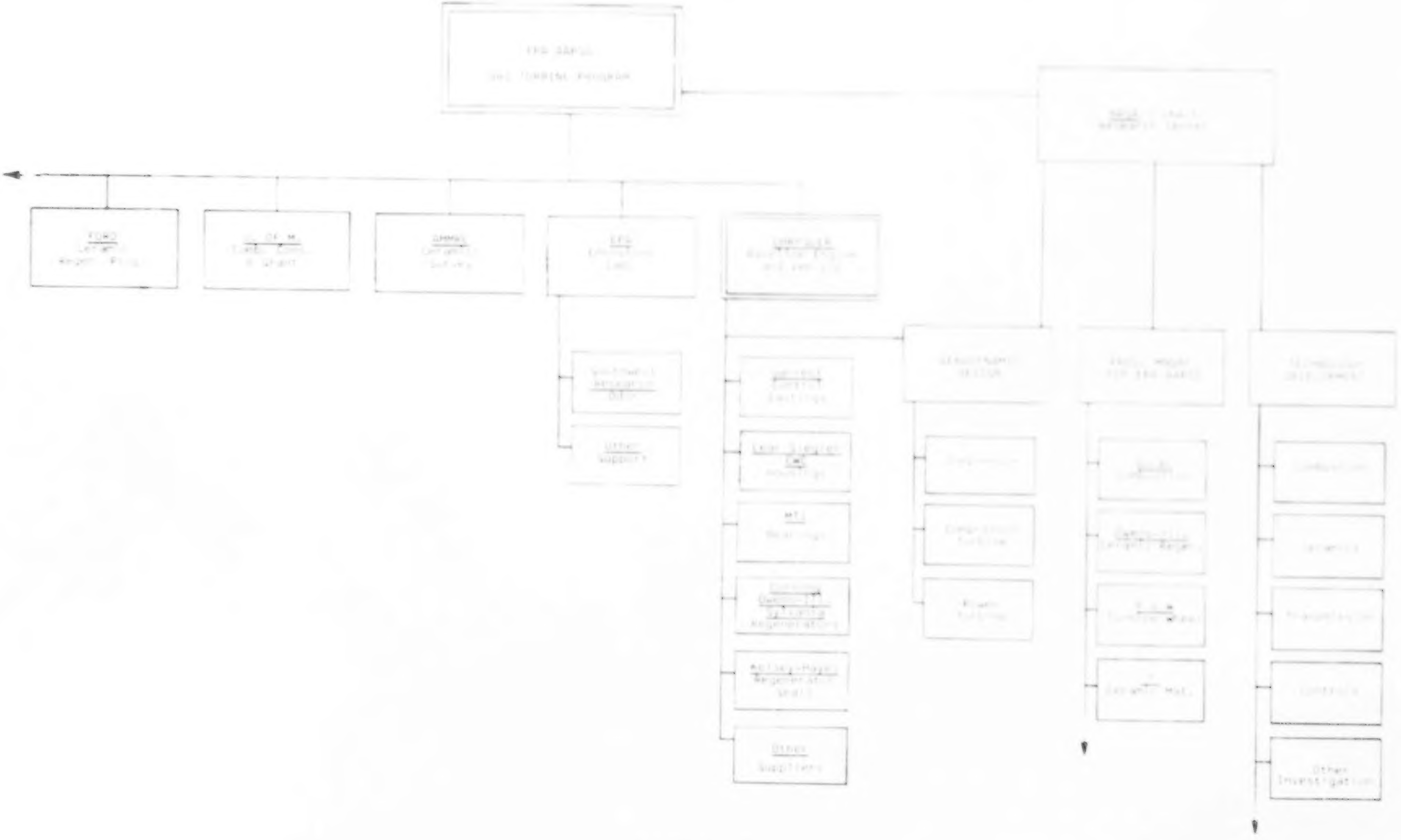


Figure 2

Also should be noted supporting activities at NASA-Lewis Research Center. Of the many alternative engines under consideration, the gas turbine draws the most interest and receives the application of best talent and expertise by NASA, which explains the increasing scope of their investigations, most of them on their "own" money.

COMBUSTION SYSTEM FOR THE UPGRADED ENGINE

The final item of note is a technical one concerning the selection of a combustion system for incorporation into the Upgraded Engine design.

As it already has been seen in Figure 3, a considerable amount of money has been spent on low emission gas turbine combustion research during the height of the "emission crisis" during the years 1970 through 1972. Out of that effort came only one combustion system with a potential, within the available program-time, for low enough emissions to warrant further work toward engine demonstration. The Jet-Induced-Circulation system developed by Solar had thus become a candidate for evaluation in the Baseline Gas Turbine Program, along with a "Proprietary" one offered by Chrysler Corporation.

Testing in a rig resembling an engine (gas generator plus heat-exchangers but no power section) has been recently concluded on both candidates with very encouraging results: the original 1976 Federal Emission Standards should be achievable by either system; and, in fact, there are now several combustors of varying complexity offering trade-offs between cost and emission performance.

Based on test results, a review in late September decided on how to proceed through the Upgraded Engine design and demonstration. It is now planned that not one, but two interchangeable systems will be incorporated. Both of these systems are from Chrysler; one is a moderately complex system (D-1) aimed at achieving the below 0.4 gram/mile NOx on the Federal Driving Cycle, and the other is a simple system (F-15) possibly capable of below 1.0 gram/mile. Although both will be built and evaluated, the primary system in 1976 will be the one which will pass the emission standards that Congress will have set for the approximate period 1976 through 1980.

From technical details to be furnished in the next section, it is evident that the Solar combustor has achieved very low steady state emissions and very wide range, better in fact than the Chrysler D-1 system has. However, to achieve this performance, the system has grown exceedingly complex (from four fueled fixed primary ports plus four fixed dilution ports to four fueled and four non-fueled primary ports plus four dilution ports, all with variable geometry). It will be seen that this complexity has brought in several cost-, operational-, and design-oriented disadvantages contributing heavily to the choice of the alternate. However, the Jet-Induced-Circulation scheme might very well be considered if very low emissions become paramount in the future, or by other applications, such as stationary powerplants, where the turndown ratio and transient requirements impose far less heavily.

In the following two sections of the report, technical progress in the major areas of the EPA/Chrysler gas turbine project will be presented.

PROGRESS REPORT, GENERAL

By C. E. Wagner

CHRYSLER CORPORATION

The EPA/Chrysler Baseline Gas Turbine Development Program is currently at the mid-point of its schedule. It was initiated about two years ago and still requires about two years to meet its objectives. Figure 4 is a milestone chart indicating both past accomplishments and future goals. Efforts to date have been principally directed towards using the Baseline Engine to evaluate and develop improvement concepts. Significant of this activity is:

- Building 7 engines.
- Building 3 vehicles.
- Running 1600 hours of cyclic engine endurance.
- Evaluating low emissions burners of both Solar and proprietary Chrysler concepts.
- Evaluating ceramic regenerators on both rigs and engines.
- Building and engine testing a pre-prototype integrated control system.
- Completing a vehicle evaluation of a torque converter lock-up device.
- Examining the Free Rotor operation of a test cell engine,

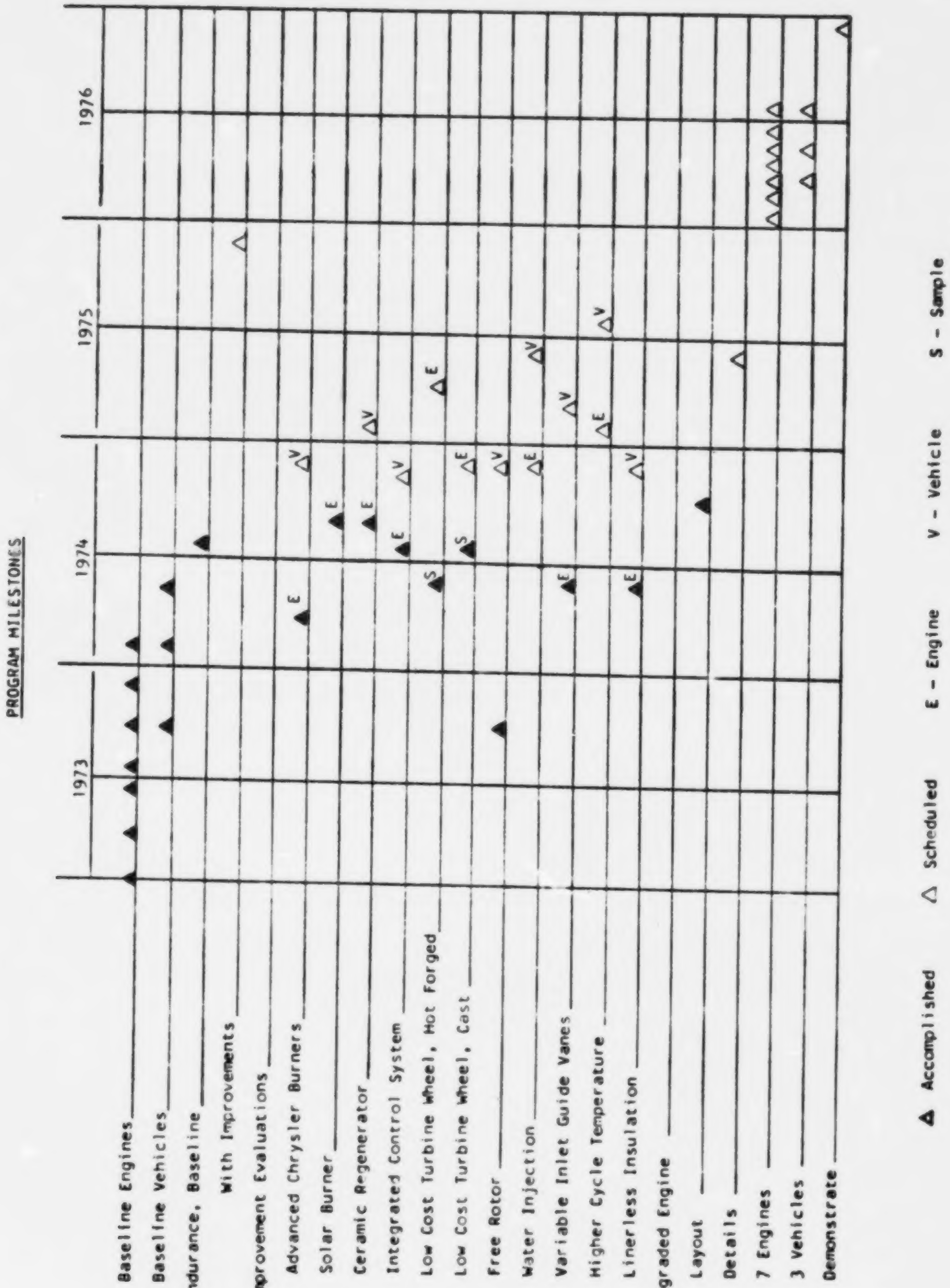

PROGRAM MILESTONES
1973
1974
1975
1976
7 Baseline Engines
3 Baseline Vehicles
Endurance, Baseline
With Improvements
Improvement Evaluations
Advanced Chrysler Burners
Solar Burner
Ceramic Regenerator
Integrated Control System
Low Cost Turbine Wheel, Hot Forged
Low Cost Turbine Wheel, Cast
Free Rotor
Water Injection
Variable Inlet Guide Vanes
Higher Cycle Temperature
Linerless Insulation
Upgraded Engine
Layout
Details
7 Engines
3 Vehicles
Demonstrate
E
V
S
▲ Accomplished
△ Scheduled
E - Engine
V - Vehicle
S - Sample

Figure 4

and designing and building a Free Rotor adaptation for Baseline Vehicle evaluation and development.

- Successfully running several hundred hours of endurance on an engine with linerless insulation.

The purpose of this Baseline development activity has been principally to provide a design base for the Upgraded Engine; and as indicated by the milestone chart, such efforts are scheduled to continue for several more months in parallel with the Upgraded Engine design.

By way of review, our overall program goals are to demonstrate an Upgraded Engine powered vehicle which:

- uses significantly less fuel than a comparable powered spark ignition reciprocating engine,
- meets the original 1976 emissions standards, and
- shows potential for being mass produced and marketed competitively.

Figure 5 is an update on Upgraded Engine and Vehicle specifications. These are shown in comparison with the Baseline, Chrysler's Sixth Generation gas turbine engine.

FUEL ECONOMY GOALS

The fuel economy improvement is the overall most important goal in that it directly effects both cost of operation and emissions. A breakdown of how this is to be achieved is shown in Figure 6. The rationale for these goals is discussed in the following.

UPGRADED ENGINE
FUEL ECONOMY IMPROVEMENT BREAKDOWN

Item	Change	Estimated Increase In Tank Mileage
1. Cycle Temperature	+42°C	5%
2. Aerodynamic Efficiency		
Compressor	+2.2 pts.	6%
Compressor Turbine	+2.2 pts.	9%
Power Turbine	+3.2 pts.	5%
3. Regenerator	+2 pts.*	--
4. Power Augmentation		
VIGV and Water Injection	23%	15%
5. Reduced Heat Losses	50%	10%
6. Intermediate to Compact Vehicle Weight	20%	20%
	Total Factor	93%

* Change results from flow reduction. Reduced flow results from efficiency improvements and augmentation.

Figure 6

BASELINE VS. UPGRADED ENGINE AND VEHICLE
COMPARATIVE SPECIFICATIONS

	Baseline	Upgraded
Power, Maximum @ 29°C	112 kW (150 hp)	92 kW (123 hp)
Power, Design Point	112 kW	75 kW (100 hp)
Engine Weight	272 kg (600 lbs.)	182 kg (400 lbs.)
Vehicle Weight	1950 kg (4300 lbs.)	1588 kg (3500 lbs.)
Time, 0-96 km/h (0-60 mi/h)	12 s	12 s
Fuel Economy, FDC	3.4 km/l (8 mi/gal)	6.4 km/l (15 mi/gal)
32-96 km/h avg. (20-60 mi/h avg.)	6.5 km/l (15.3 mi/gal)	11.4 km/l (26.9 mi/gal)
Emissions, FDC	Original 1975 U.S. Standard	Original 1976 U.S. Standard (Current 1977)
HC	.255 g/km (.41 g/mi) 1.08 g/kg fuel	.255 g/km (.41 g/mi) 2.02 g/kg fuel
CO	2.11 g/km (3.4 g/mi) 8.95 g/kg fuel	2.11 g/km (3.4 g/mi) 16.75 g/kg fuel
NOx	1.864 g/km (3. g/mi) 7.89 g/kg fuel	.249 g/km (.4 g/mi) 1.97 g/kg fuel
Design Point		
Pressure Ratio	4.1	4.1
Airflow	1.04 kg/s (2.3 lb/s)	.61 kg/s (1.342 lb/s)
Turbine Inlet Temperature	1010°C (1850 °F)	1052°C (1925 °F)
L.P. Regeneration Inlet Temperature	730°C (1350 °F)	765°C (1403 °F)
Gas Generator RPM	44,600	58,500
Power Turbine RPM (Stress)	45,700	70,000
Maximum Power (Augmented)		
Pressure Ratio	———	5.0
Airflow	———	.75 kg/s (1.65 lb/s)
Turbine Inlet Temperature	———	1052°C (1925 °F)

Figure 5

Temperature Increase

In the Baseline Engine, temperature is limited both by the turbine wheels and the regenerator. Efficiency-response optimization results in the turbine wheels being designed to their stress limit. Baseline wheels are cast of 713-C alloy. The 42°C increase in temperature of the Upgraded Engine can be withstood in similarly stressed designs by utilizing one of the improved nickel-based alloys currently available (Figure 7).

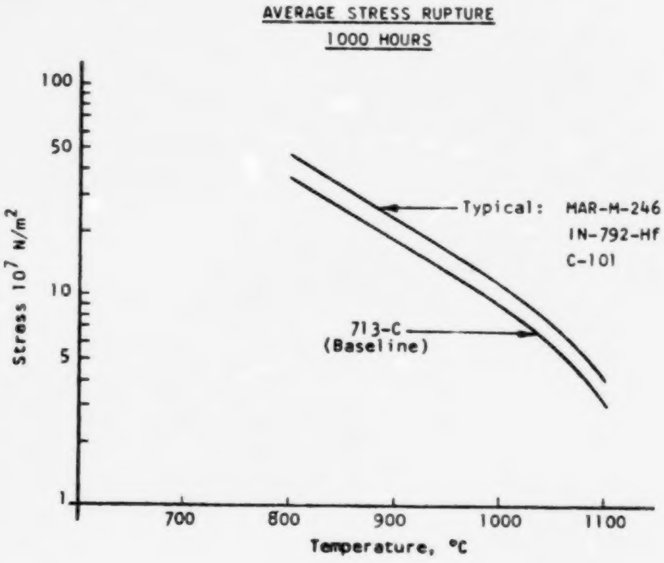


Figure 7

The Baseline regenerator is of 430 s.s. stock brazed and coated for oxidation protection. Serious deterioration occurs above 730°C. By changing to a ceramic material for the Upgraded Engine, we are confident that life will be adequate for an Upgraded Engine demonstration. However, to demonstrate full automotive life potential, it is still necessary to solve the well publicized problems associated with sodium and sulfur attack. Based on the current level of understanding and current efforts in the areas of coatings and material alterations, we are also confident that an early solution to these problems is forthcoming.

Improved Effectiveness and Aerodynamic Efficiencies

Changes in these parameters relative to Baseline values are shown in Figure 8. The improvement in compressor efficiency is based on changing the impeller from radial to a 30° backsweep design. Material will be aluminum with a steel inducer. A completed mechanical analysis has shown that strength/deflection/polar-moment-of-inertia requirements can be met. Parts for this program will be machined from forged blanks.

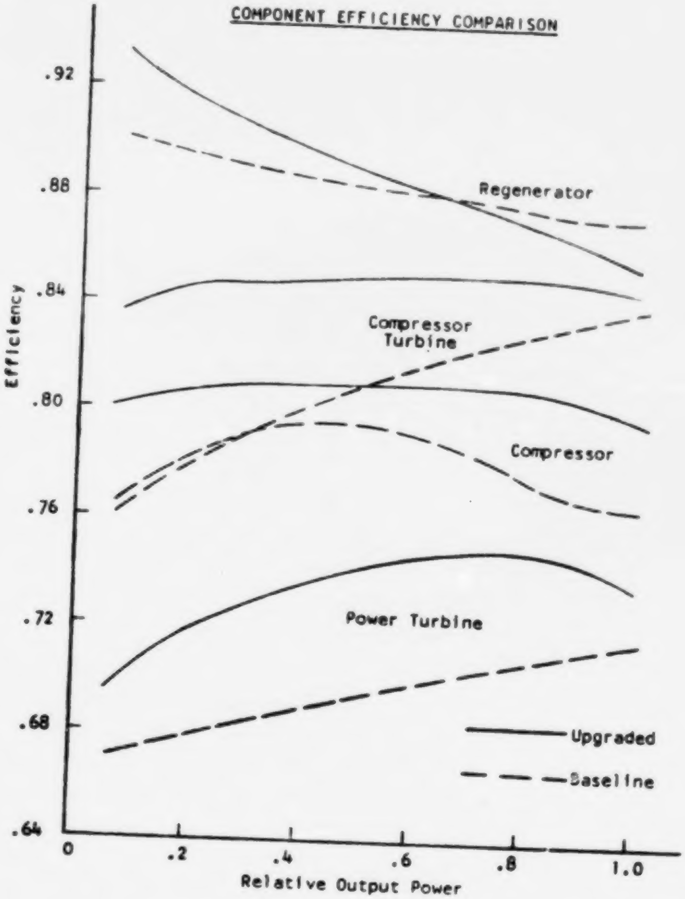


Figure 8

The improvement in compressor turbine efficiency results from lowering the work speed parameter ($\Delta H/U^2$) from 2.4 to 2.1 and biasing the blade leading edge angle to reduce low speed incidence. Both the compressor and compressor turbine are higher inertia designs than their Baseline Engine counterparts; however, because of scaling effects, we still expect to realize a small improvement in gas generator response time.

The improvement in power turbine efficiency results from a reduced interstage loss. The divergence of this passage has been reduced, and the lower compressor turbine work speed parameter has reduced the inlet velocity level.

A higher regenerator effectiveness in the power range where most vehicle driving is done, is being accomplished by increasing the relative regenerator size and using a ceramic regenerator. The major increase is attributable to the relatively steep rise of ceramic regenerator effectiveness with a flow reduction. However, it should be pointed out that engine flow reductions result from improvements such as higher temperatures, higher efficiencies, power augmentation, etc. Regenerator size is actually limited by vehicle installation constraints; and without the flow reducing improvements, a loss in fuel economy could result. Such was the case when ceramic regenerators were substituted directly into a Baseline Engine as shown in Figure 9. The close agreement shown between actual and predicted BSFC in changing from metal to ceramic provides confidence in the predicted performance for the Upgraded Engine.

BASELINE ENGINE TEST
METAL VS. CERAMIC REGENERATOR
BSFC VS. OUTPUT POWER CHARACTERISTIC

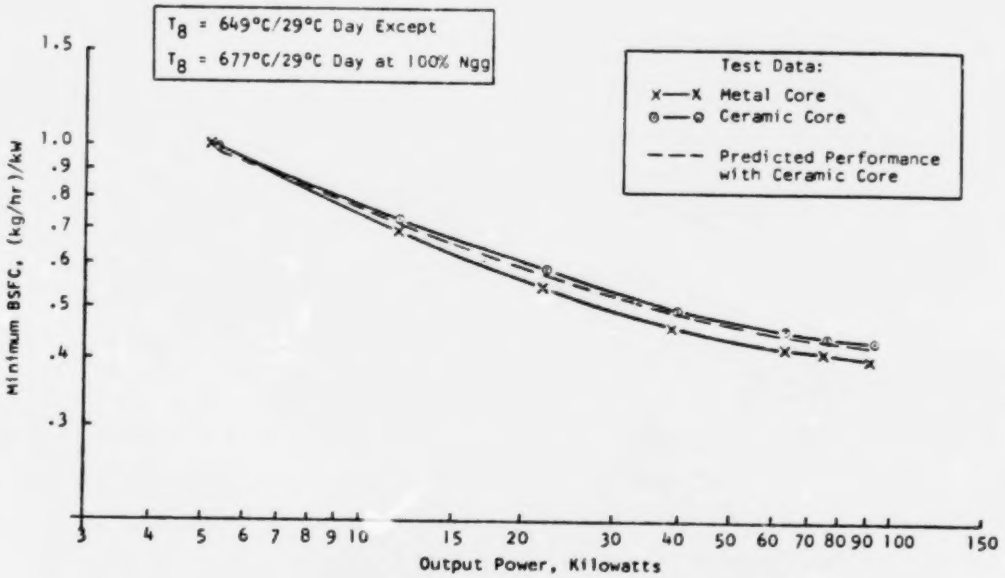


Figure 9

Torque Converter Lock-Up

Tests verifying these small improvements were documented in our last Quarterly Report. Its most significant benefit is an improvement in engine braking.

Power Augmentation

The Upgraded Engine design has been sized assuming that a 23% augmentation goal will be met. A fuel economy benefit is thereby assured. However, if the goal is not met, reduced vehicle performance will result. Tests to date on the Baseline Engine with variable inlet guide vanes have not assured us that the prediction for the Upgraded Engine can be met (Figure 10). The best 100% speed augmentation to date without increasing turbine inlet temperature is about 3.5%. A modified compressor inducer section is currently being prepared in an attempt to improve this. The combined effect of VIGVs and water injection has not yet been determined.

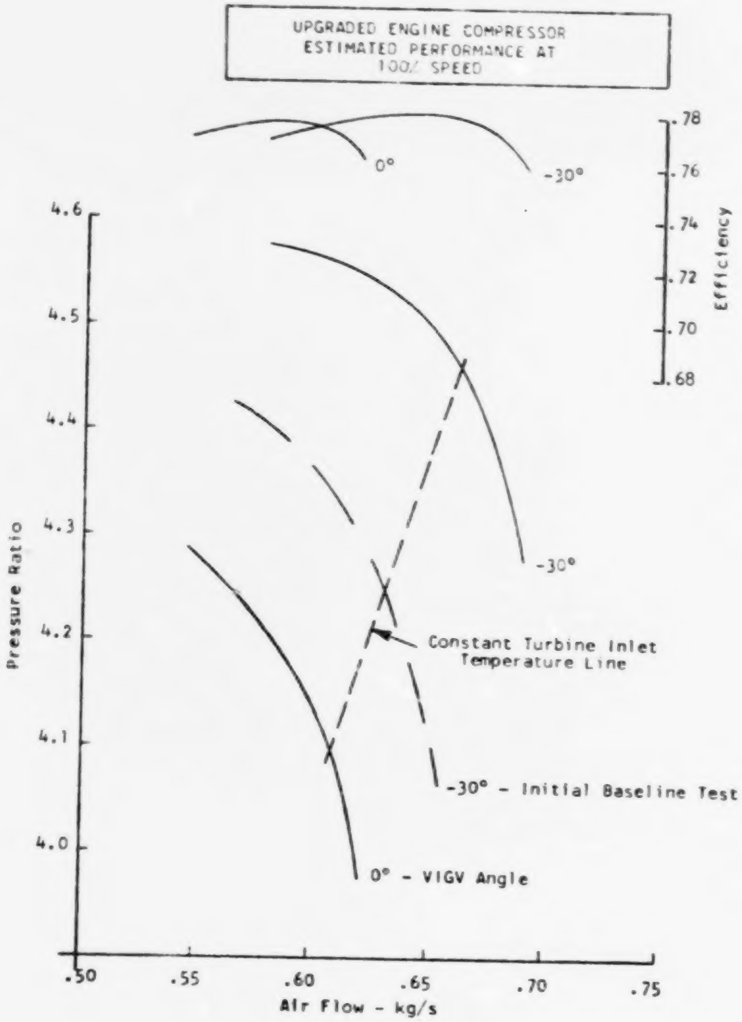


Figure 10

The Upgraded Engine compressor of itself should respond better to VIGV augmentations as a result of being designed with a relatively larger inlet means radius and a backward curved impeller. Additionally, the lower work speed parameter compressor turbine wheel should hold its efficiency level better under the increased loading with augmentation.

Aside from augmentation and as shown in Figure 11, VIGVs provide a method of low power (50% speed) engine control with at least a slight improvement in fuel economy. More important, however, is the control of very low powers without cooling the engine. This is essential to maintaining low CO emissions, and also should provide a fuel economy savings in cyclic engine operation such as required by the Federal Drive Cycle.

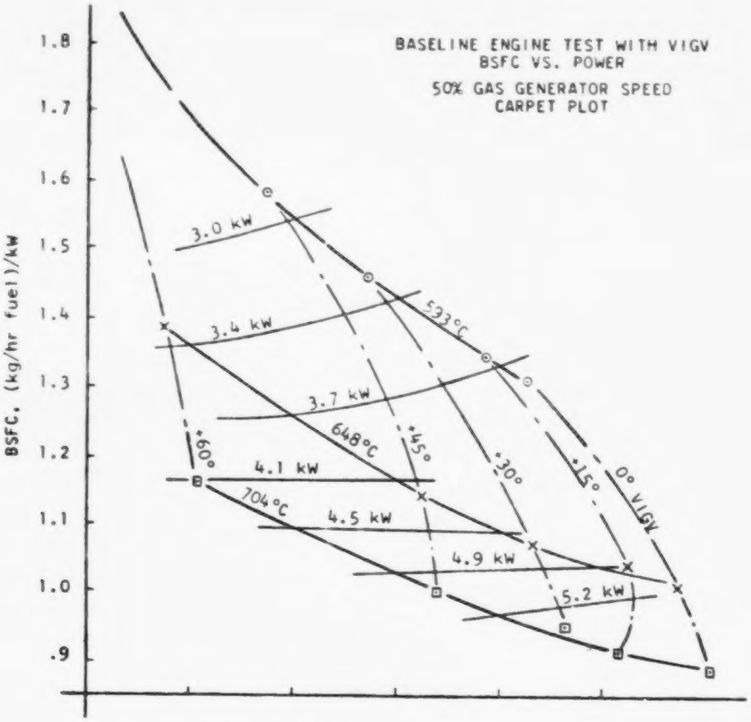


Figure 11

Reduced Parasitic and Heat Losses

The potential for this improvement is based on indications of excessive heat loss in the Baseline Engine. NASA, as part of their support to this program, is currently running heat balance tests to assess both the magnitude and identify the source of these losses. However, with the design of the Upgraded Engine currently underway, items are already being incorporated which should contribute to an improvement in this area. These include:

1. One instead of two regenerators (less peripheral heat loss area).
2. Reduced number of oil bearings and an oil sump remote

from housing surface (less oil heat rejection).

3. One-piece housing casting (reduced housing flange heat loss).

Intermediate To Compact Vehicle

The improvement here results from a 20% reduction in engine size as permitted by a 20% reduction in engine weight.

EMISSIONS GOALS

As mentioned in the EPA introduction to this report, two interchangeable combustor concepts, D-1 and F-15, have been selected for the Upgraded Engine. Both of these concepts have resulted from proprietary efforts of Chrysler separate from this government contracted activity; and as yet, mechanical details cannot be made public. Shown in Figure 12 are the F-7 Baseline burner and the Solar burner. The F-15 will be close in size and complexity to the F-7; while the D-1 in its present concept, though larger and more complex, is compatible with Upgraded Vehicle engine compartment size limitations (Figure 13). The current Solar concept is not yet developed to the point of a typical underhood installation. Its steady state emissions, as shown in Figure 14, are excellent. Not shown on this curve are values for the proposed F-15 concept. NOx, however, is about the same level as the F-7; while CO is slightly below the level of the D-1. Shown on Figure 15 is a breakdown of the contribution to the FDC NOx level from the various Federal Drive Cycle modes of operation. Estimates for the Upgraded Engine are based on the assumption that fuel economy goals will be met and that equivalent ppm can be achieved in a scaled down size. As Figure 15 shows, in the improved system, most of the NOx is generated during gas generator acceleration. During this mode, which represents about 6% of the total FDC elapsed time, the fuel rate is about four times its steady state level. Emissions values under these conditions are estimated from transient tests as shown in Figure 16.

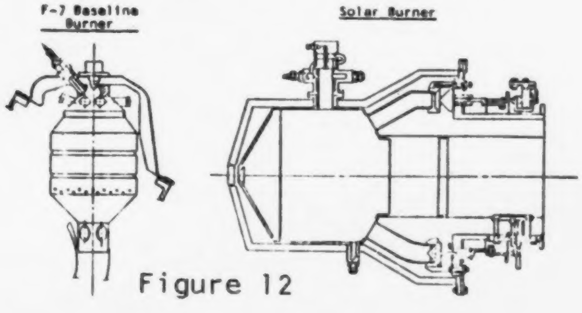


Figure 12

UPGRADED ENGINE
VEHICLE INSTALLATION MOCK-UP

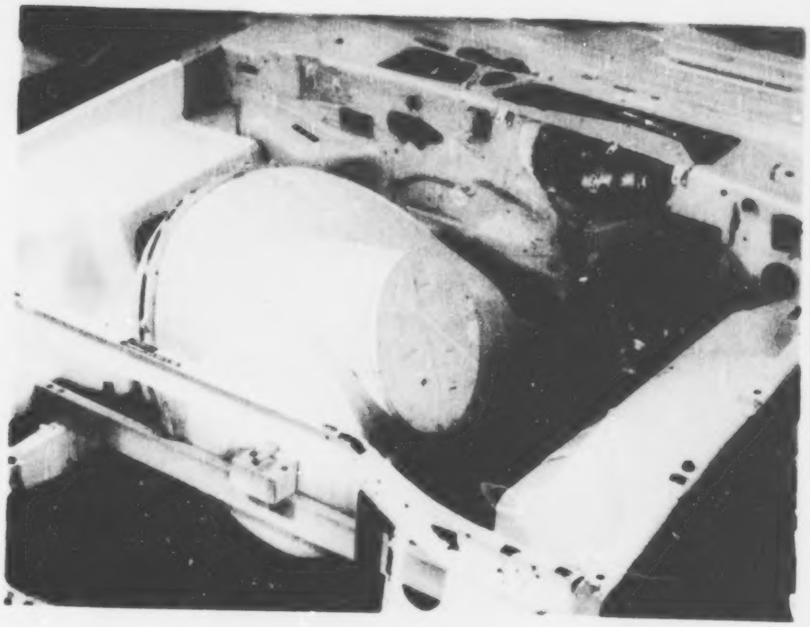


Figure 13

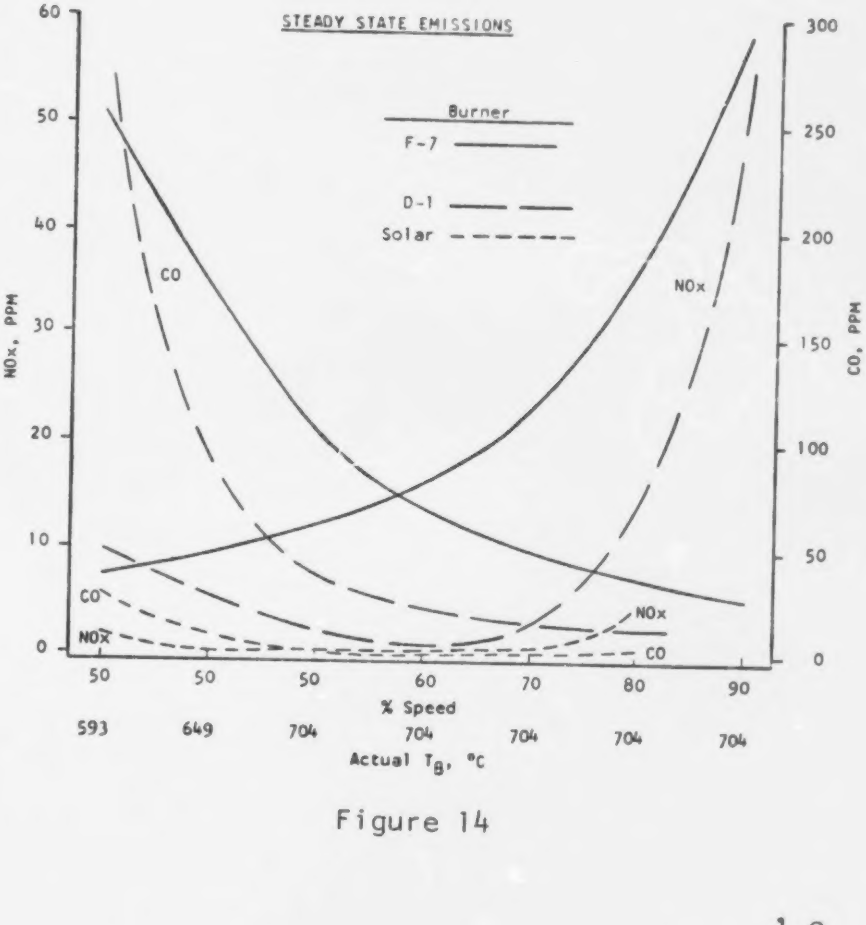


Figure 14

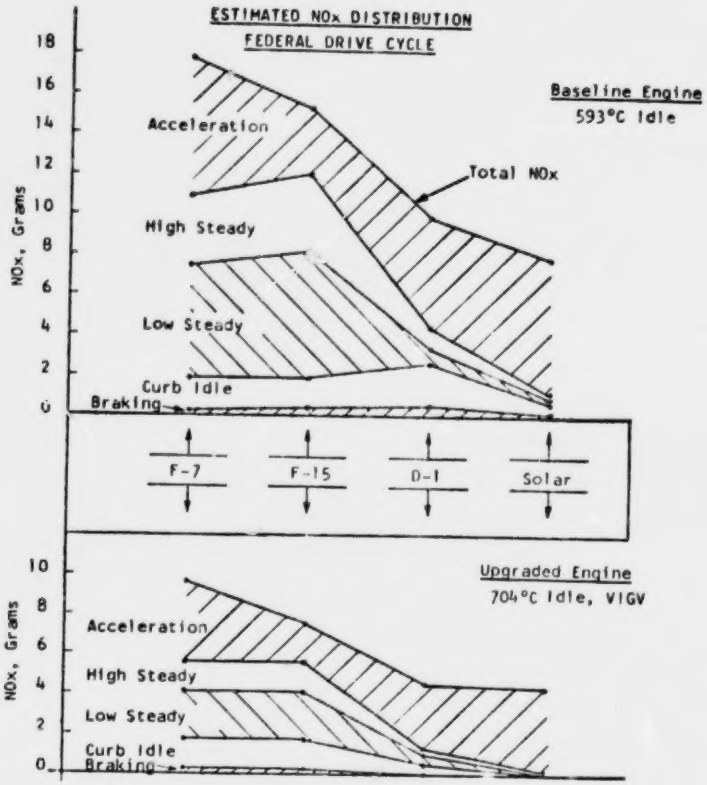


Figure 15

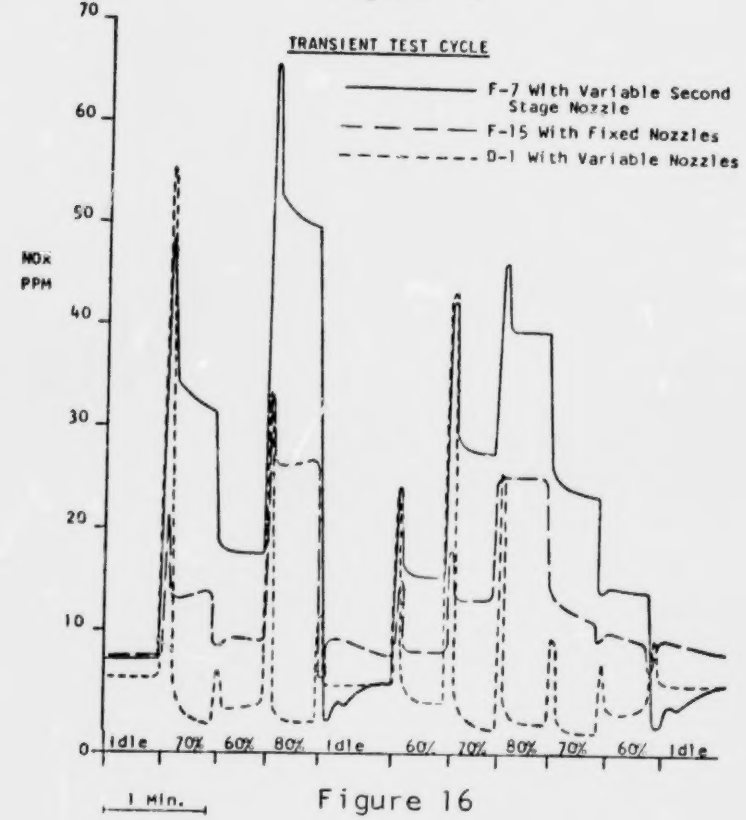


Figure 16

In the case of the Solar burner, the variable geometry control system has not yet been developed to where such transient tests can be conducted. The acceleration NOx value of Figure 15 was therefore based on projections from extremely limited data.

The D-1 system is in a relatively early stage of development. It gives promise of providing a substantial improvement, especially in NOx control, based on the steady state and transient test results as shown in Figure 14-16. It requires some improvements in both starting and transient operation before vehicle verification tests can be conducted.

Average Baseline Vehicle test results for the F-7 burner on the 12.5 km FDC are:

	CO g/km	NOx g/km
	2.7	1.4
Current Goal, 1977 Standards	2.1	.24

Projecting to Upgraded Engine conditions, no problem in meeting the CO goals is foreseen. However, it is anticipated that even with development of the promising D-1 concept, extremely close control of all engine variables will be required to meet the NOx goal.

Omitted to this point is any mention of hydrocarbon emissions control. As discussed in our Fifth Quarterly Report, a negligible concentration exists at steady state operation for any of the above burners. However, if the flame is extinguished during gas generator decelerations, enough HC will be formed during relights to amount from .6-.9 g/km on a Baseline Engine. Providing for a pilot flame during deceleration has been demonstrated to be a sure method of control, but improved relight quality is still very much a development goal.

PROGRESS REPORT, INTEGRATED CONTROL SYSTEM

By L. Lewis

THE GARRETT CORPORATION

Meeting the objectives of the engine program will be strongly influenced by the characteristics of the control system. While there is ample evidence that gas turbines can be adequately controlled, witness aircraft propulsion engines, the ability to control the engine and meet all the engine objectives within the automotive economic base has yet to be demonstrated. For this reason, a joint program between Chrysler Corporation and The Garrett Corporation of California was started in October 1973 with the objective of establishing the design of a fully integrated engine control sysrem.

The program is basically structured in three phases:

- Analyze engine control requirements.
- Design and develop preprototype control system for Baseline Engine.
- Design control system for Upgraded Engine.

Progress to date has been primarily in the first two phases in that a preliminary analysis of the control system requirements has been performed and the results translated into a preprototype system design. Three preprototype systems have been fabricated and are presently undergoing engine testing at Chrysler.

The control functions incorporated in the preprototype systems are summarized in Figures 17 and 18.

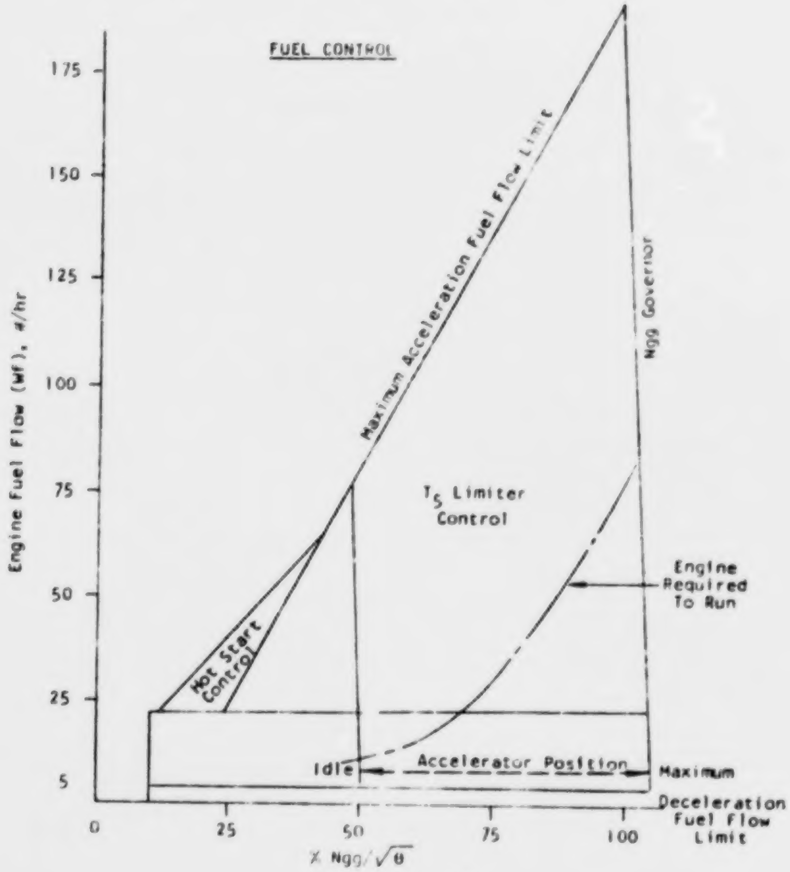


Figure 17

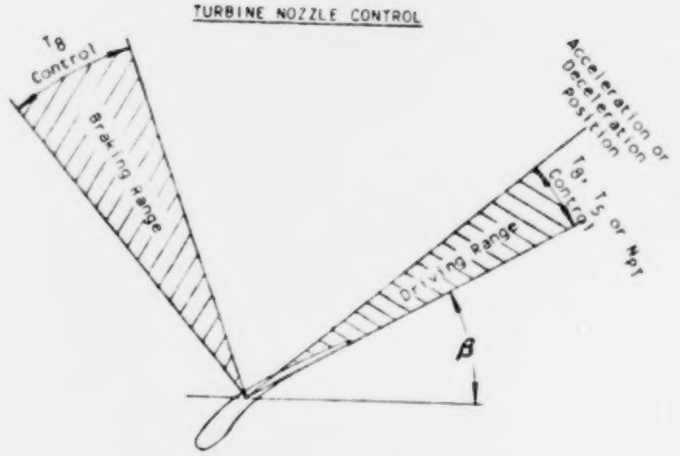


Figure 18

Fuel control functions include provisions for gas generator speed control from 50% through 100%, the set point being a function of accelerator pedal position. Acceleration control is provided by two means, viz. an open loop maximum fuel schedule functioned by $Ngg/\sqrt{\theta}$ together with closed loop control over maximum T5. Deceleration control is effected by limiting minimum fuel flow to 5 #/hr.

Nozzle control function falls into the two categories of driving and braking modes. In the former, control is effected by setting the nozzle to control either T8 or T5 to a preset datum, corrected to T_A. In the latter case, the nozzle is set to maximum braking consistent with non-exceedence of T8 maximum.

Fully automatic start sequencing is provided which ensures the correct sequencing of events throughout the start cycle.

The preprototype system (Figure 19) is basically a full authority electronic approach utilizing a D.C. motorized pump as the fuel system. The electronic controller controls the velocity of the D.C. motor, hence engine fuel flow. Nozzle position is controlled through use of an electro-hydraulic actuator. Test results to date have included generation of all control functions and demonstration of all control functions.

Present activities on the program are being directed towards the Upgraded Engine control, specifically in the area of cost.

Symbols:

T5 - Turbine Inlet Temp.	Ngg - Gas Generator Speed
T8 - Low Pressure Regen. Inlet Temp.	N_{PT} - Power Turbine Speed

AUTOMATIC START CONTROL

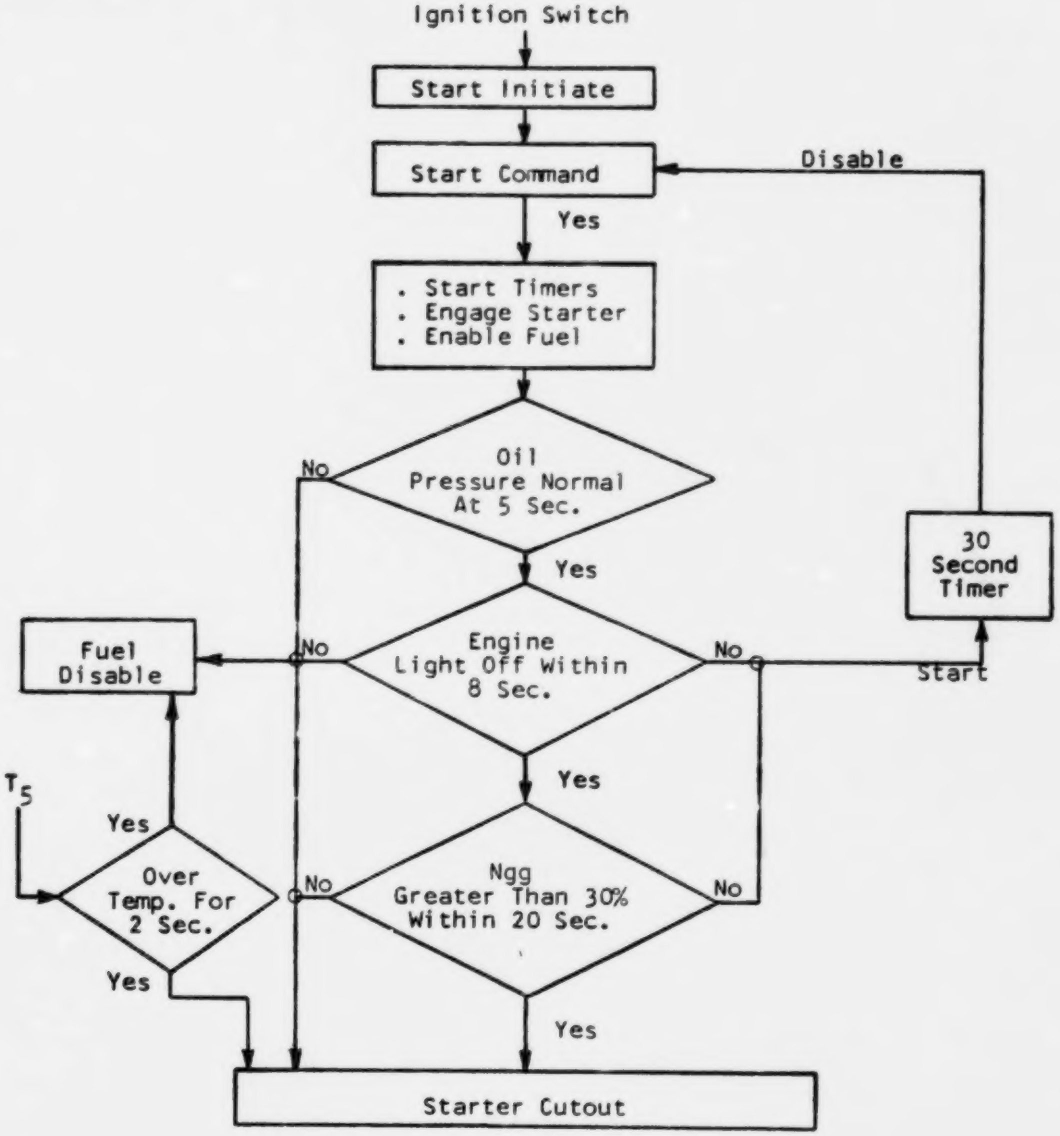


Figure 19

Development of the Nissan Gas Turbine

Keijiro Kinoshita

Principal Research Engineer, New Power Source Research Dept.,
Central Engineering Laboratories, Nissan Motor Co., Ltd.

Natsushima-cho, Yokosuka 237, Japan

In this paper mainly the later progress of the engine development and several experimental results of the exhaust emission control study are described. At first the mechanical troubles were solved, then the aerodynamically components were improved. In a fuel control system, the closed loop turbine inlet temperature control system was used. The exhaust emission cleans the California's thirteen mode for heavy duty vehicles.

1. Introduction

The early details of the Nissan gas turbine development were reported at Tokyo Joint International Gas Turbine Conference in 1971, then the control system was presented at the Gas Turbine Conference in 1973.

In this paper mainly the later progress of the engine development and several experimental results of the exhaust emission control study are described.

2. Engine Development

In 1968 the first engine was manufactured and the present engine named YTP12 has been manufactured as the fourth stage improvement. Until now not a few mechanical troubles have had occurred and been solved.

At first, a blade crack of the compressor impeller occurred and by increasing the rigidity of the blade so that its natural frequency may be raised this problem was solved. Then, in the early stage the vibration troubles frequently occurred, and this also solved by enlarging the size of the high speed rotatory shaft and bearings in order to raise its critical speed. The rigidity of the main housing was also increased.

The second trouble of the engine vibration has occurred later, and this time an elastic supporting construction for the high speed bearing is adopted to solve it.

The other major mechanical problem was the trouble of the regenerator parts, and this detailed development is found later. To settle the heat distortion of the engine hot parts such as the turbine shroud, a thermal expansion releasing mechanism was adopted, and the uniformity of gas temperature distribution at the turbine inlet was obtained.

After having solved these mechanical problems, the engine endurance driving test is now being carried out to achieve more than 1,500 hours life which is the target in a few years later.

3. Engine Specification

The Nissan gas turbine is a regenerative two shafts type with variable power turbine nozzles. The cross-sectional view and its appearance are shown in Fig. 1 and Photo. 1 respectively.

The specified item of the YTP12 gas turbine is shown as follows:

Air flow	2.0 kg/s
Compressor pressure ratio	3.90
Maximum output	280 PS
Continuous output	235 PS
Maximum torque	14.5 kgm
Turbine inlet temperature	920 degree C

Design specific fuel consumption	220 g/PS-h
Gasifier max. speed	40,000 rpm
Gasifier idling speed	20,000 rpm
Power turbine max. speed	30,000 rpm
Output shaft max. speed	3,400 rpm
Size w/o transmission,	length 1,230, width 1,160, height 980 mm
Weight w/o transmission	640 kg
Compressor efficiency	80%
Compressor turbine efficiency (total-to-total)	87%
Power turbine efficiency (total-to-total)	87%
Combustor efficiency	99.8%
Combustor pressure drop	5.0%
Regenerator speed	20 rpm
Regenerator effectiveness	80%
Regenerator leakage	4.7%
Regenerator pressure drop	11%
Fuel	Kerosene

4. Aerodynamical Development

As to the aerodynamical performance, the compressor efficiency was improved first and the turbine performance was matched to it, then the pressure loss of the gas flow passage and the gas leakage from the regenerator's rubbing seals were improved, and as the result of their improvements, the engine output reached its objective power.

Compressor Development

The aerodynamical design of the centrifugal compressor has been based on the calculation of the relative velocity distribution in the blade row. The relative Mach number at the inducer tip was kept within the transonic range, and the impeller geometry, such as size of hub and shroud and blade configuration, were determined reasonably.

The impeller consists of fifteen main blades and fifteen splitter blades and is made of aluminum alloy integrate precision cast.

The diffuser consists of thirteen channels which are made by machining an aluminum forged plate.

In the first stage the expected air flow rate and pressure ratio had never been obtained from the initial designed impeller. Then many improved impellers of which inducer edge and the shroud contour were cut or modified were machined and tested.

In the diffuser development, many modified vaned diffuesers were machined, that is, shape of the leading edge was wedge type or logarithmic spiral curve and their inlet angles were variously set. Some combination of the impeller and the diffuser showed good performance after many compressor tests.

Fig. 2 shows the progress of the compressor performance obtained by many test. Photo. 2 shows the test rig in which a 440 KW direct current dynamometer is used. Fig. 3 shows the map of the best performance compressor.

Turbine Development

The gasifier turbine and the free turbine are both axial flow type and their rotors are made of Incornel 713C integrate precision cast.

After the turbine performance test, the height of the gasifier turbine blade was modified to make match its flow characteristic to that of the compressor. In spite of this good matching of gasifier components, engine output was less than design horse power. So the flow passage parts were further developed as follows.

Turbine Diffuser Development

In the flow passage parts, an interstage diffuser between the gasifier turbine and the power turbine, and a power turbine diffuser connected with the turbine shroud were the most difficult parts to develop.

As to the initial designed parts, a flow separation occurred and the pressure loss were not small in both diffuser, consequently engine output was unsatisfactory.

Therefore various kinds of their models were made and many tests were carried out in order to remove the separation and to lower the pressure loss. As a result of this development each pressure loss of the inter stage diffuser and power turbine diffuser has been able to be less than 3% respectively. One percent loss is equivalent to about five horse power. Fig. 4 shows the configuration of the diffuser and test results. As to the power turbine diffuser the one with splitter vanes showed the best performance. Thus, the pressure loss improvement of 3% x 2 was equivalent to 30 horse power up and the reduction of regenerator leakage loss rate 4.3% was equivalent to 30 horse power, which is described later, consequently the engine output has reached its objective power.

5. Regenerator Development

Settling of the Mechanical Trouble

The construction of the regenerator is shown in Fig. 5, that is, the regenerator core is supported by a center hub and is driven by a pinion through the ring gear which is fixed to a periphery of the core.

In the center supporting shaft bearing and pinion shaft bearing an oil-less lubrication is adopted, and a lubrication of gearing for the pinion and ring gear is also oil-less one. The rubbing seal is a bellows type and, of course, its rubbing shoe is oil-less surface.

At the beginning of the regenerator development a great many mechanical troubles occurred in case of applying it to the engine. Above all, the breakage of the expensive glass ceramic matrix core was a painful trouble.

This problem was perfectly solved, however, after many experiments over one year by two means. The one was taking compressed air into the area of the core periphery so that the core may be pressed externally. The other was remaking the plate springs attached to a core periphery improving their shape and materials so that their elastisity may moderate the impact due to gear driving.

After that, the durability for wear of the oil-less parts previously mentioned became to be a subject of development. Many kinds of materials were tested, and at present satisfactory results are obtained by using a special carbon for a bush and a sulphurized tool alloy steel for gears.

Wear of the rubbing seal surface has been one of the troublesome problems, but it is confirmed experimentally that a special carbon shows good characteristic for cold side seal. For the hot side seal a blend of nickel-oxide, calsium-fluorid and some sort of metal oxide are sprayed to its surface.

As to the rubbing seal further troubles are followed such as an unstability of air leakage at engine starting, a breakdown of welding position of thin-plate due to sudden heating, and a separation of the sprayed layers on the seal surface. These troubles are now being solved experimentally.

Photo. 3 shows a ceramic core and Photo. 4 shows a bellows seal and new type carbon seal.

Improvement of Leakage Loss

In a regenerative gas turbine amount of the leakage loss in the regenerator greatly influences on an engine performance, for example 1% of leakage will be equivalent to about 7 horse power down. Though the leakage loss must be reduced, this ploblem is considerably difficult to solve like as that of wear for rubbing seal surface.

Fig. 6 shows the leakage loss rate to an air flow rate through a core. From this figure it is known that the leakage loss rate at design point of engine is 4.7% in the bellows type, the other hand the value of 3.2% is obtained in a new type seal. A carry-over loss and a leakage loss through the core wall are both included in above loss.

Because of difficulty to measure an amount of leakage loss directly in an operating engine, a leakage test rig which simulated engine operating condition was manufactured This is shown in Fig. 7, and the test result by this device keeps fairly good accuracy.

6. Fuel Control System

As the YTP12 gas turbine has a variable power turbine nozzle, the engine is controlled by a fuel flow and a nozzle angle.

As to this control of the fuel flow and the nozzle angle, the open loop control system had been used in former time. (1)

At present a closed loop electronic control system is used in the Nissan gas turbine in consideration of its control accuracy and easiness to adjustment. The schematic diagram of this control is shown in Fig. 8.

In this control system, a fuel flow rate is regulated automatically so that the gasifier speed (Ngg) may become to be its set speed (NggSET), and an opening angle of the vari able nozzle is also regulated automatically so that the turbine inlet temperature (T7) may become to be its pre-set temperature (T7SET) by each feed-back control system respectively.

The set value of the gasifier turbine inlet corrected temperature (T7SET*) is previously fixed as a function of each gasifier corrected (Ngg*) with due regard to the surge margin, acceleration, and the fuel consumption. These value set into the function generator of the control system, and Fig. 9 shows this set value.

Furthermore, in time of engine starting, rapid acceleration and engine braking, the variable nozzle is set at one's most suitable position to each required condition. This control system also has a starting sequence control and warning circuits.

7. Combustion and Exhaust Emission

Emission Control of Actual Engine

In almost all vehicular gas turbines, an inlet temperature of the combustor is always high owing to its regenerator effect, therefore CO and unburned hydrocarbon (UHC) will decrease, but NOx will increase substantially.

When we reduce NOx thoroughly, it will be necessary to use ultra lean primary zone combustion system, in which fuel and air are pre-mixed and burned in order to realize lean homogenous combustion. This new type combustor is now under development in our laboratories.

In case of this report, the conventional combustor was used to engine combustion test.

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(1) K. Kinoshita : "Development of the Nissan Motor Gas Turbine . . . . .", ASME Paper 73-GT-54, April, 1973

Fuel Injector Test

As to the swirl type fuel injector, the relation between its performance and exhaust emission is shown in Fig. 10, 11 and 12. From these figures it is seen that NOx is not affected by a fuel injector but CO and UHC are fairly affected by its characteristic, especially in case of part load of the engine. This means that a fine atomization of fuel at part load is very important condition for CO and UHC emission reducing.

As for the fuel injector which must operate alone in wide range fuel flow rate such as in case of vehicular gas turbine's one, it is required to have a satisfactory characteristic of atomization covering whole load range of its engine.

Liner Test

As to the exhaust emission control, the design concepts of the liner used for our present gas turbine are early quenching and lean primary combustion. To find optimum allocation of air hole keeping the liner outer size constantly many test liners were prepared. The air hole area ratio primary zone to secondary zone of each liner was increased step by step as shown in Fig. 13.

Photo. 5 shows one of the test liner.

Fig. 14, 15 and 16 show respectively the exhaust emission test result of CO, HC and NOx for each area ratio test liner. As is evident from these figures, NOx decreases to one third according to the increase of primary zone hole area, from 7D-1 to 7G-6, on the other hand CO and UHC greatly increase. In reducing CO and UHC, however, to enlarge the liner volume, to elongate the residence time and to finish after burning by the excess oxygen are good means of settling this problem. As a result of these experiments, it is said that the air hole area allocation of 7D's one will be best in view of exhaust gas emission and combustion stability.

Exhaust Emission of Multi-Fuel

We have tested some various kinds of fuel besides kerosene, using the liner 7D. Methanol, emulsion of kerosene and water, and three dimensional mixed oil of kerosene, water and methanol are tested, and their test results are shown in Fig. 17, 18 and 19.

First, the NOx emission in case of methanol is fairly low, one fifth of kerosene's one, while CO and UHC become to increase. The reason of low NOx emission in methanol combustion is considered that CH_3OH becomes to be $CO + 2H_2$ due to thermal decomposition, and CO and H_2 are both able to be burnt in the very lean mixture, consequently the growth of NOx will be restrained. As to the high emission of CO and UHC

compared with kerosene combustion we consider that the reason is as follows:
The calorific value of methanol is about one half of kerosene, so its fuel flow is required twice of kerosene's one. Therefore, another fuel injector had to be used of which atomization ability would be insufficient and the primary air hole area ratio of the test liner would be too large and not optimum. But it is not necessary to consider these problem seriously, they will be solved easily. Thus, methanol fuel may be considered to be one of the interesting low emission fuel.

In case of the emulsion of kerosene - water, NOx emission reduction rate is only one half even if the restrain to growth of CO and UHC will be sacrificed. Furthermore in view of combustion stability, it seems to be difficult to require it more NOx reduction. When we compare it with direct water injection method, the emulsion is superior in fairly less water amount to water injection method.

In case of three dimensional mixed oil, kerosene, water and methanol, the tendency of NOx reduction is similar to the former case, that is, however loosen CO and UHC control, NOx emission do not decrease.

There is scarcely effect due to methanol addition, and compared with the kerosene - water emulsion, NOx emission rather decrease according to its increased water composition, and CO and UHC fairly increase as kerosene - water emulsion does.

Thirteen mode test result

After every experiment previously mentioned, P-2 fuel injector, 7-D liner and kerosene fuel are chosen and used to the YTP12 gas turbine. The exhaust emission test following the California's thirteen mode test of diesel heavy duty vehicle were carried out by YTP12 engine.

The test result is as follows:

	YTP12	California, 1975 (To be expected)
CO	5.1 g/PS-h	25 g/PS-h
UHC + NOx	4.9 g/PS-h	10 g/PS-h

This California's regulation will be most severe at present for heavy duty vehicle, and YTP gas turbine clears it well. However, it has not been much time from we started the detailed combustion development, and its further study is necessary for our gas turbines.

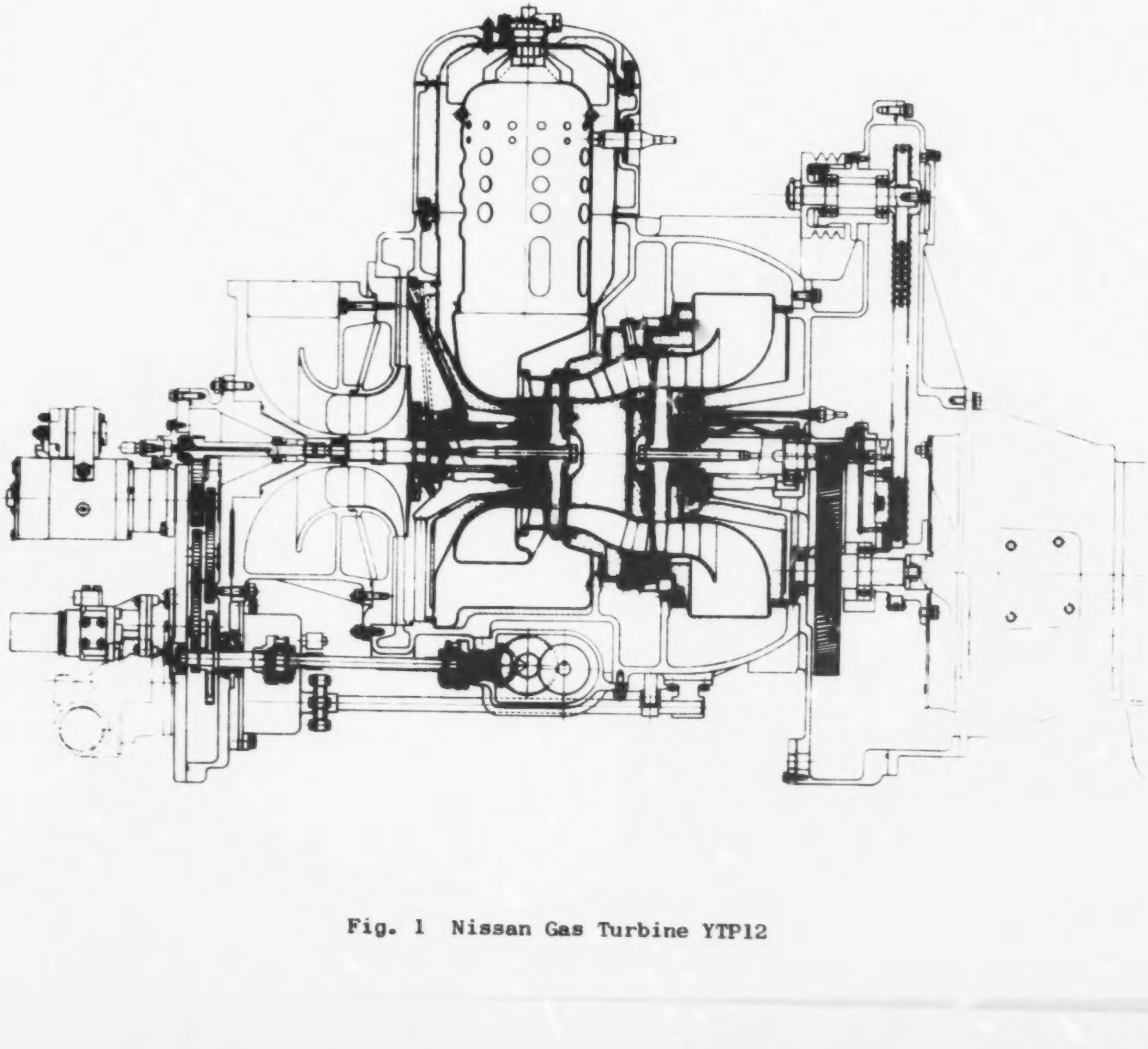


Fig. 1 Nissan Gas Turbine YTP12

IMPROVEMENT OF COMPRESSOR PERFORMANCE

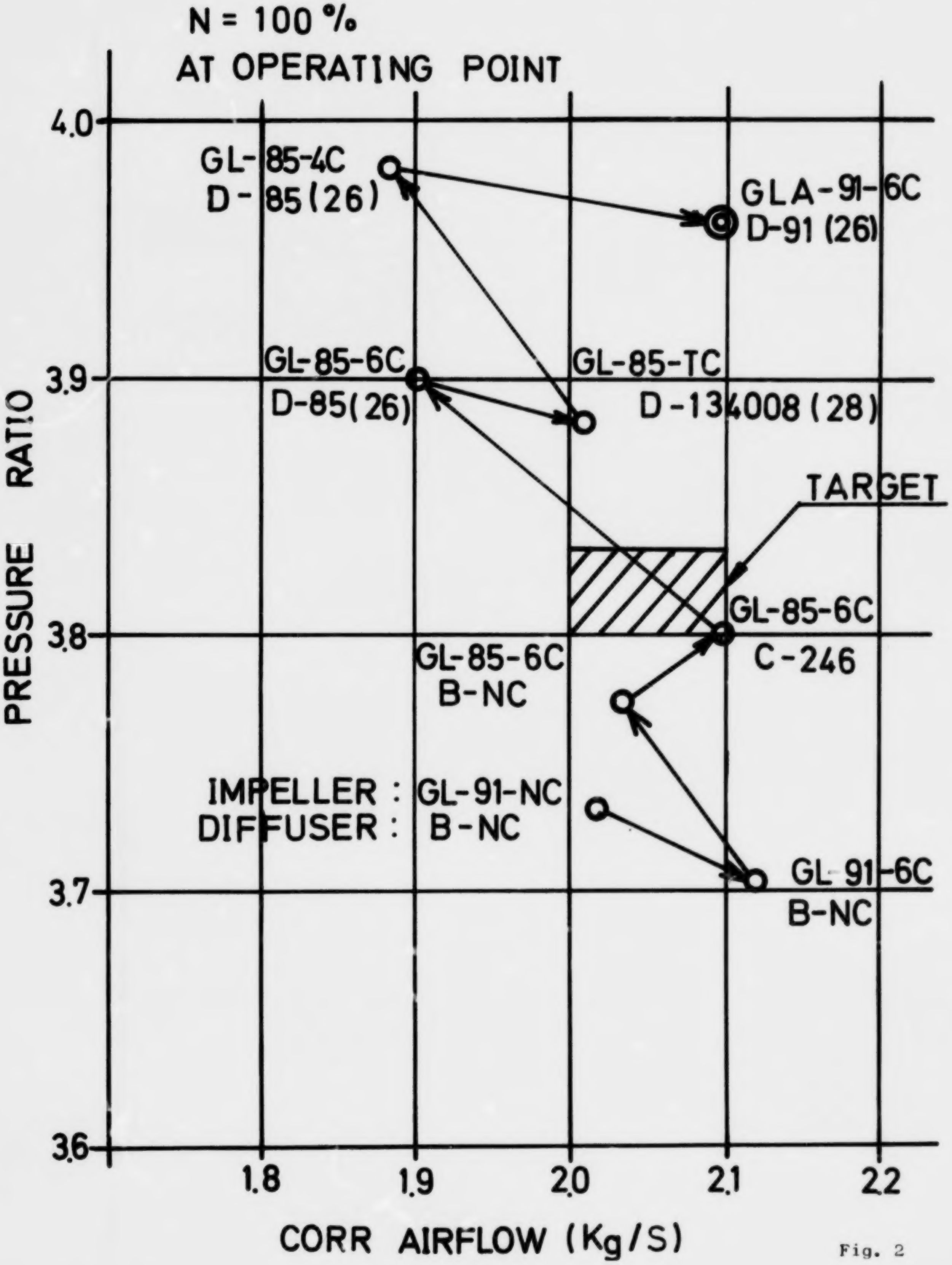


Fig. 2

COMPRESSOR PERFORMANCE

IMPELLER	GLA-91-6C
DIFFUSER	D-91(26)

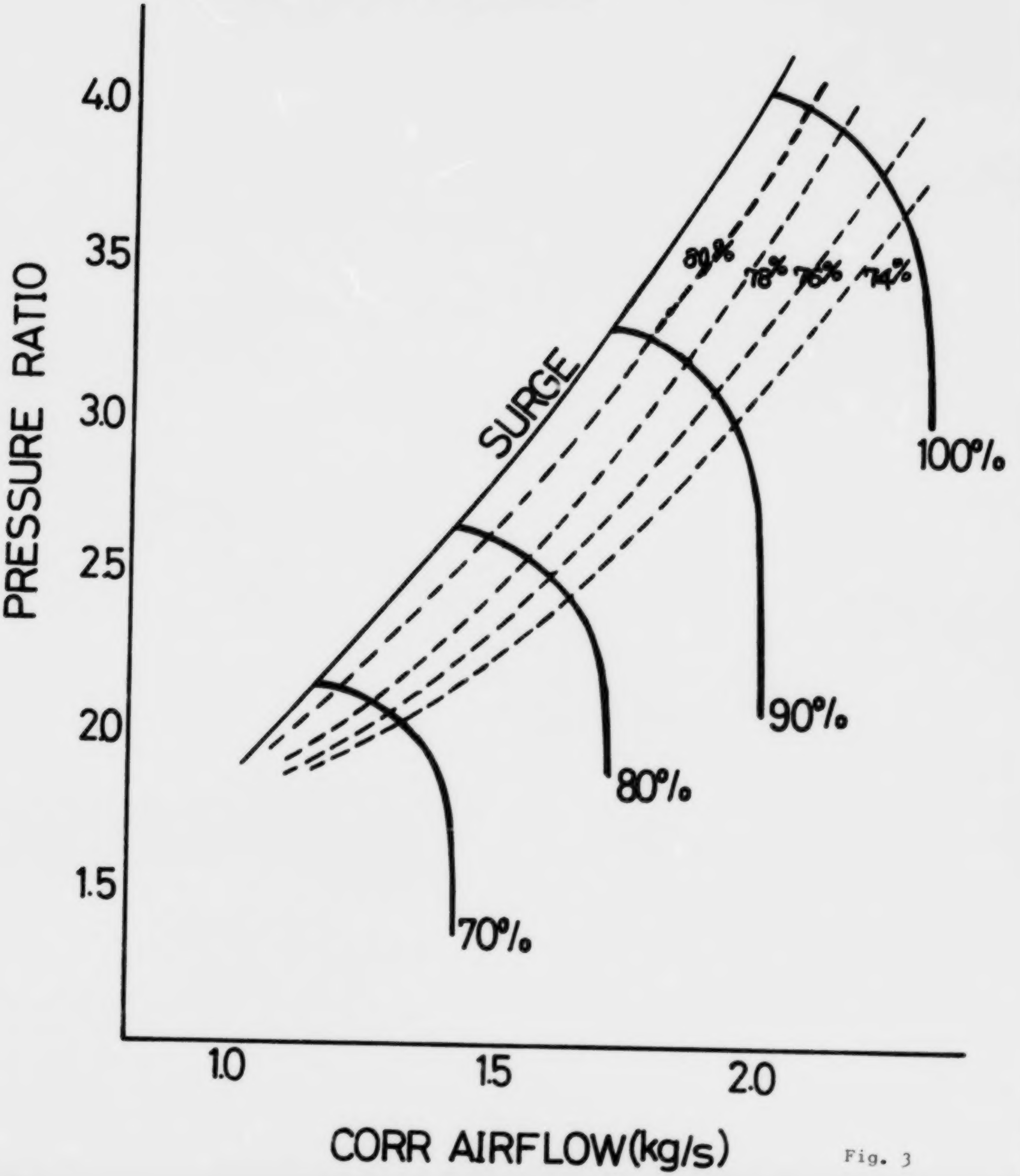
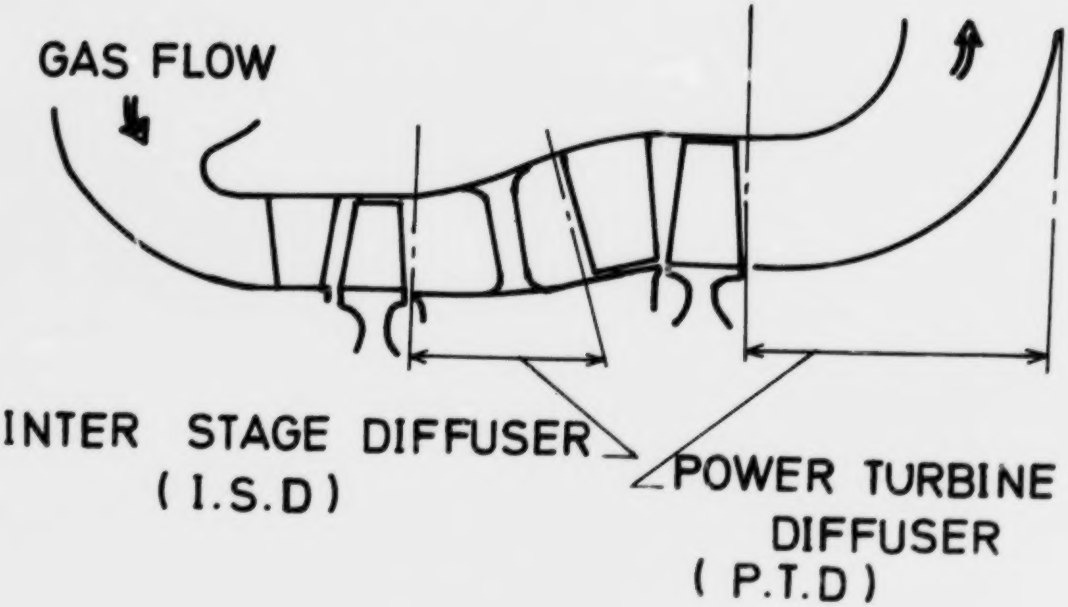


Fig. 3

IMPROVEMENT OF FLOW PATH



PRESSURE LOSS

	ORIGINAL	IMPROVED
I. S. D	8 %	5 %
P. T. D	7 %	4 %

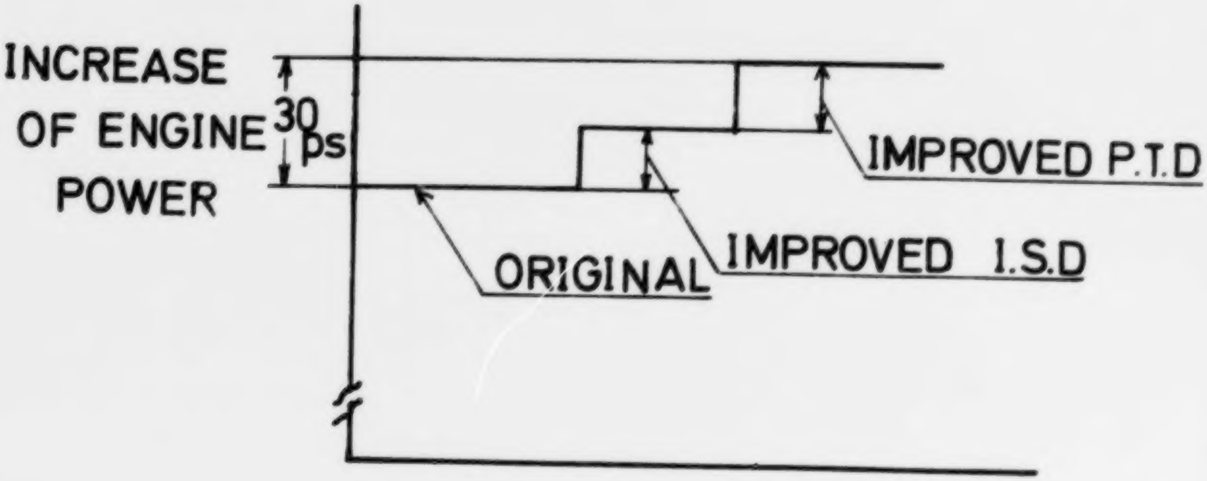
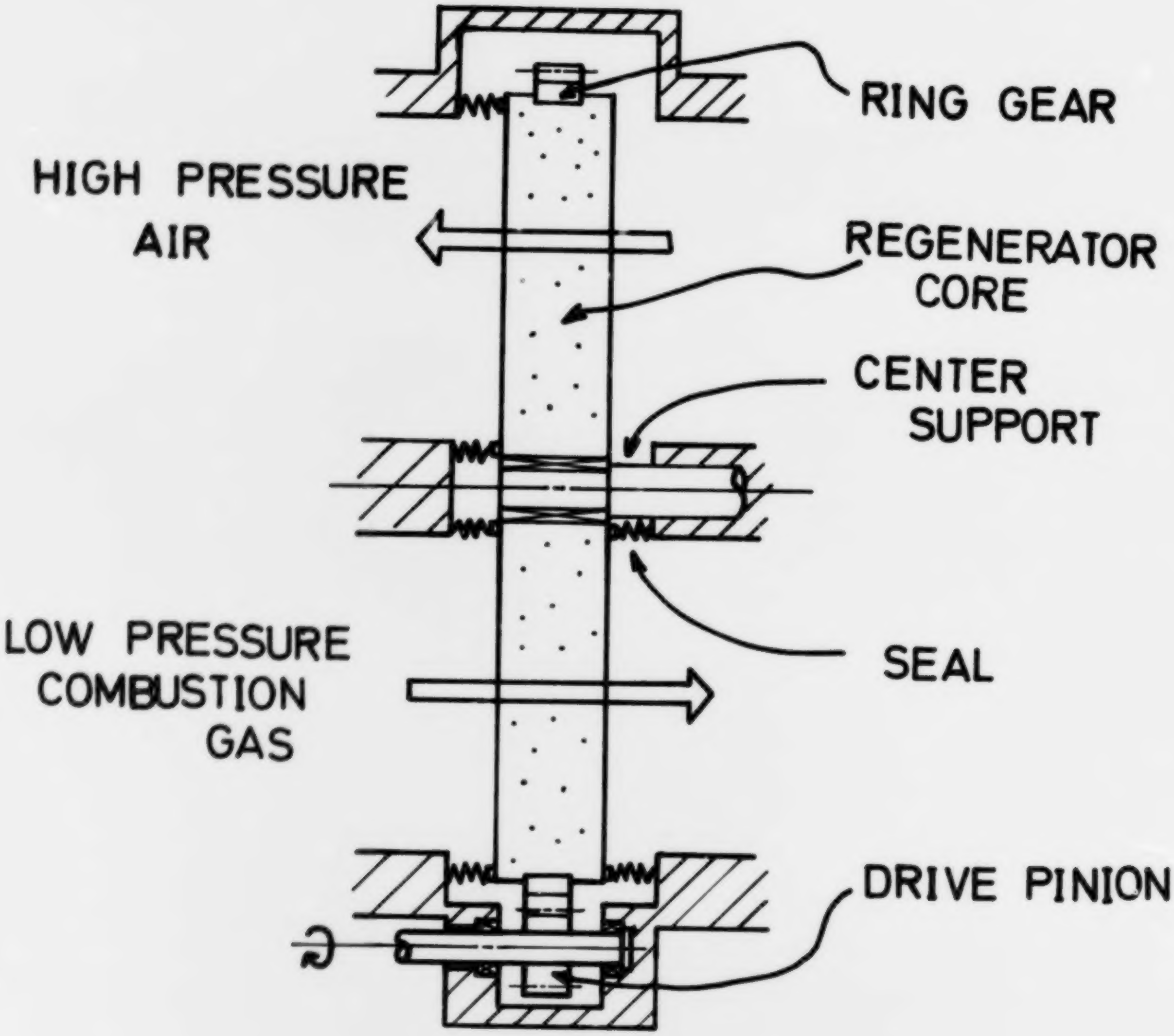


Fig. 4



CROSS SECTION OF HEAT EXCHANGER

Fig. 5

REGENERATOR LEAKAGE

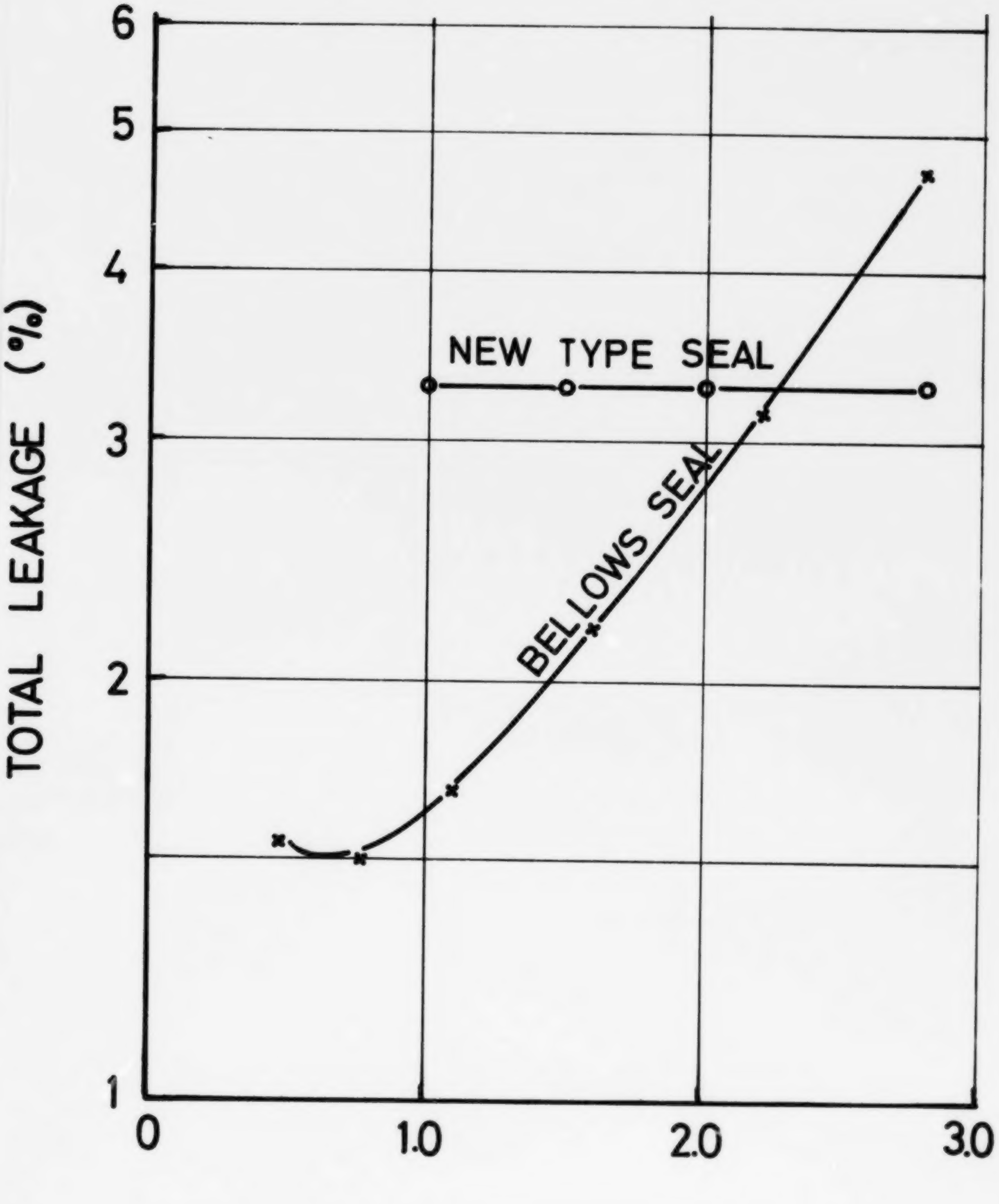
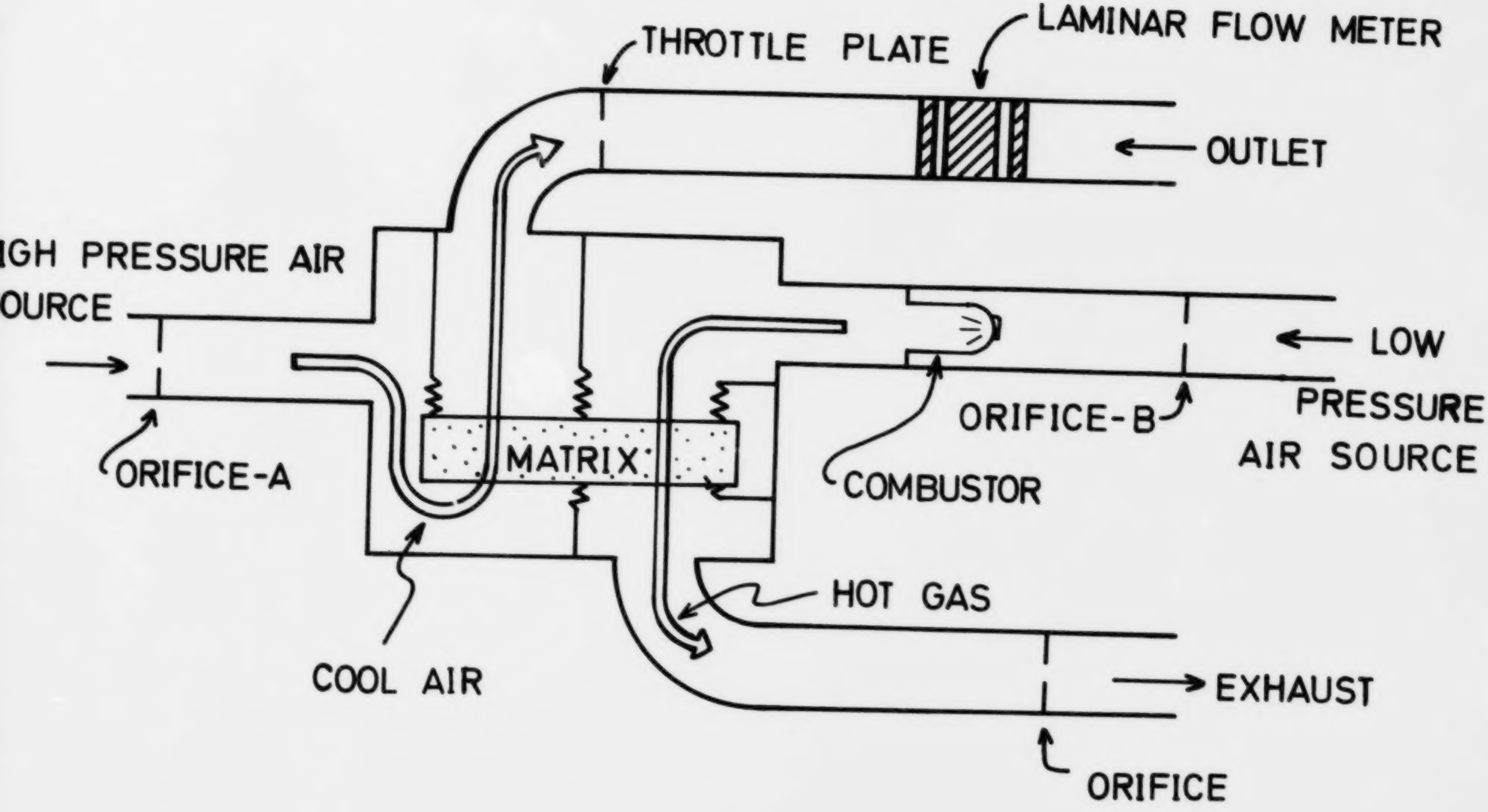
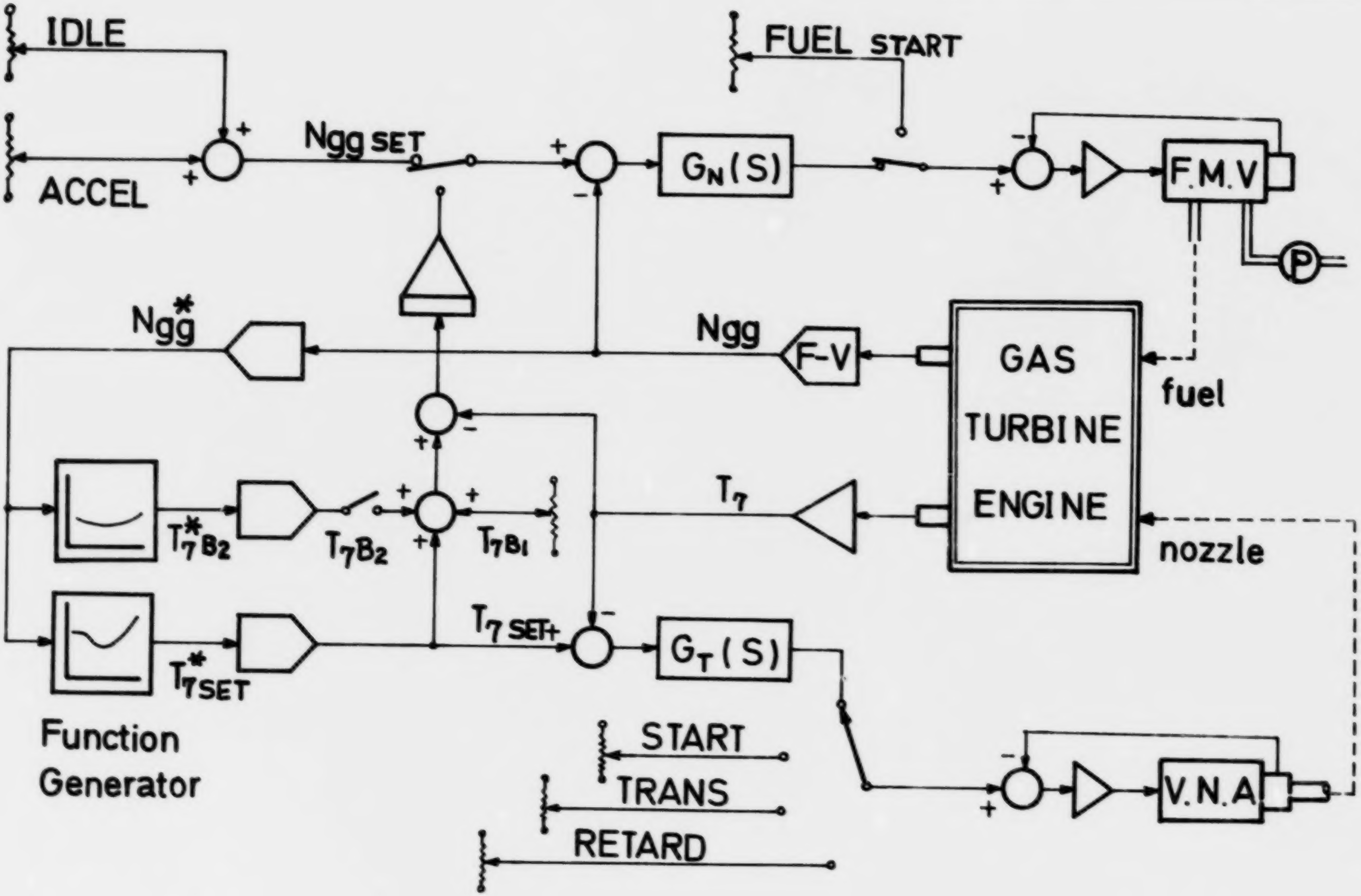


Fig. 6 INLET AIR PRESSURE (Kg/cm²G)

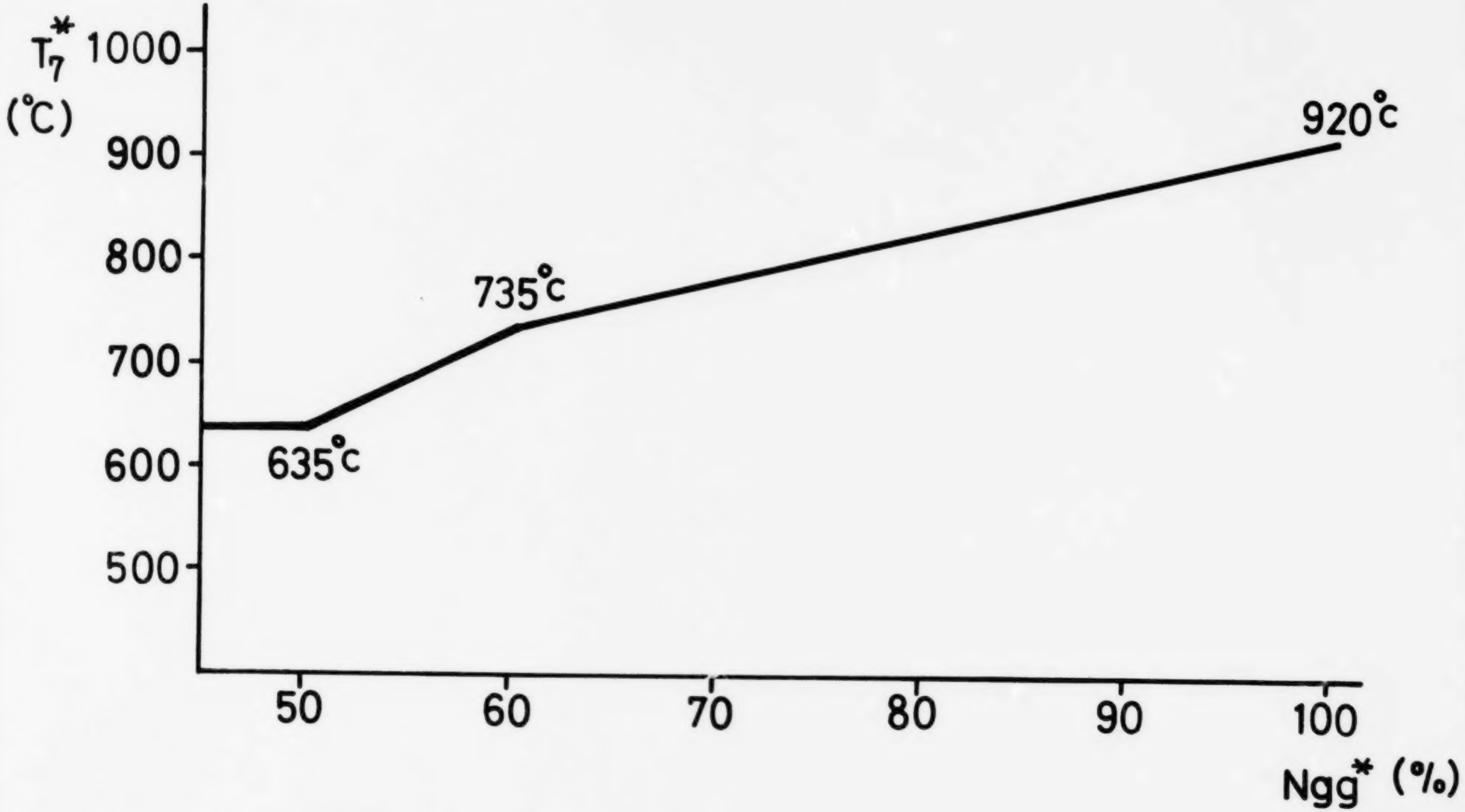


SCHEMATIC DIAGRAM OF SEAL LEAKAGE TESTER



BASIC CONTROL SYSTEM

Fig. 8



TEMPERATURE SCHEDULE (STEADY STATE)

Fig. 9

CO. UHC. NOx EMISSION

(FUEL NOZZLE)

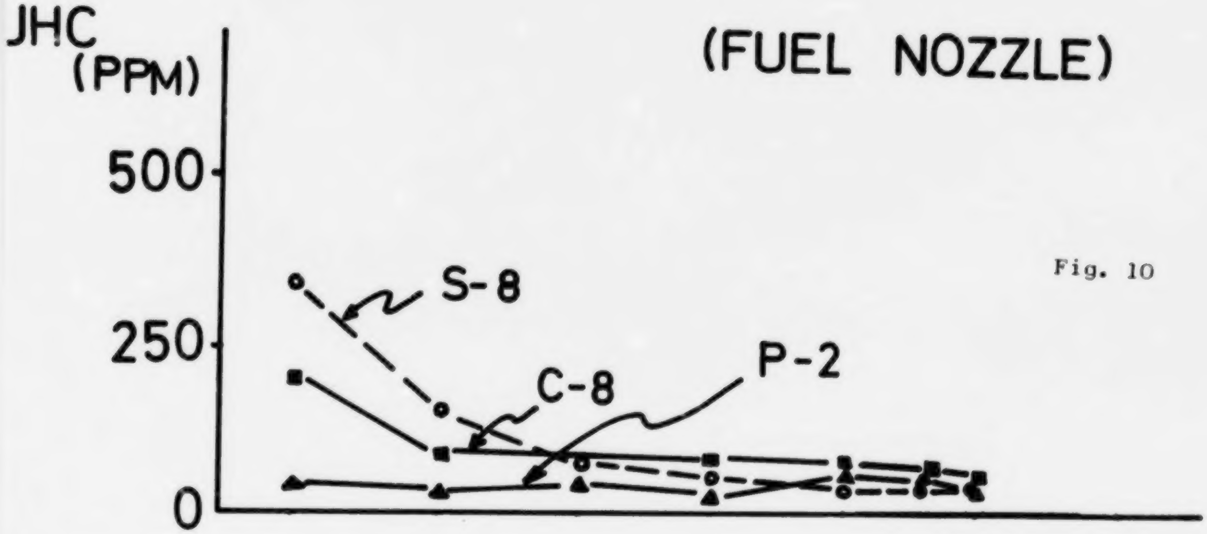


Fig. 10

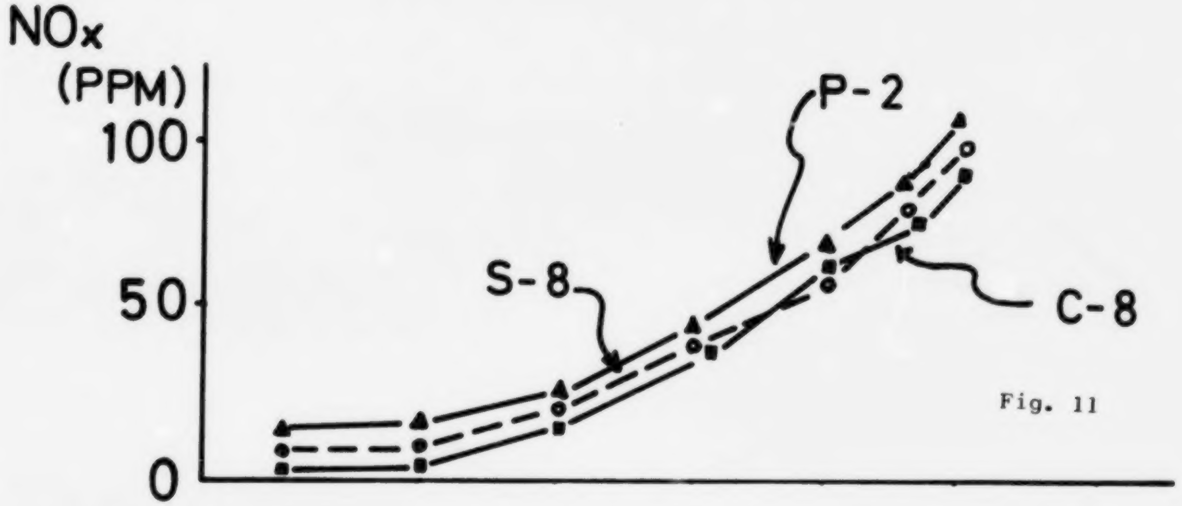


Fig. 11

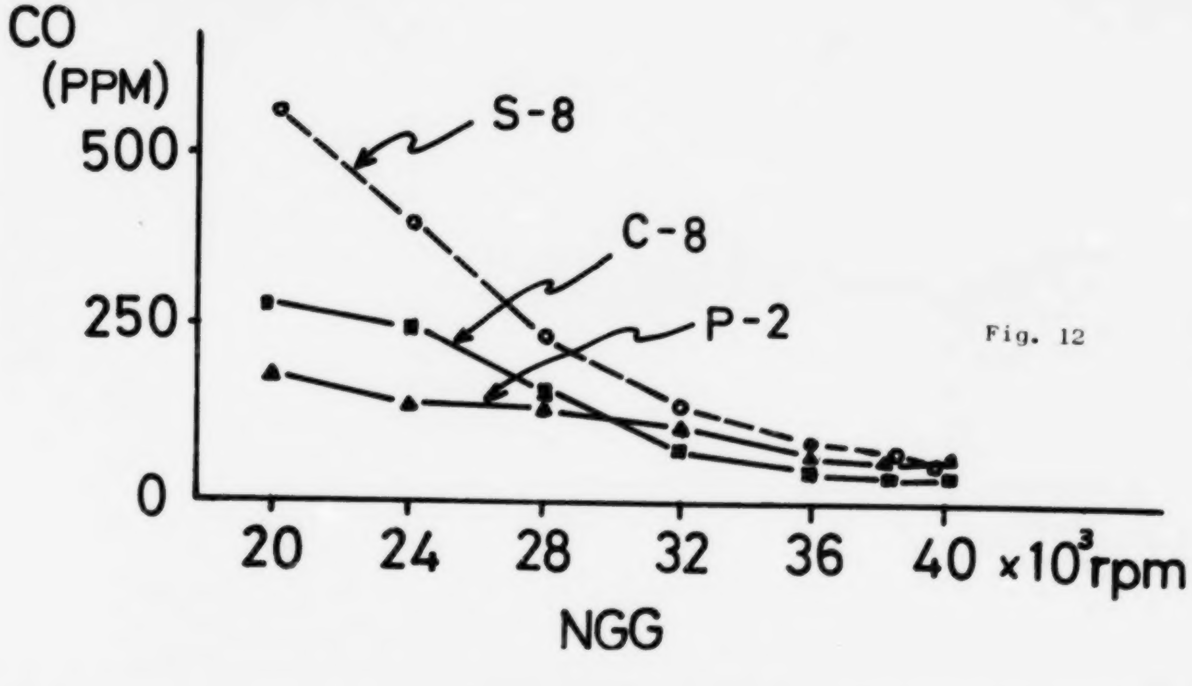
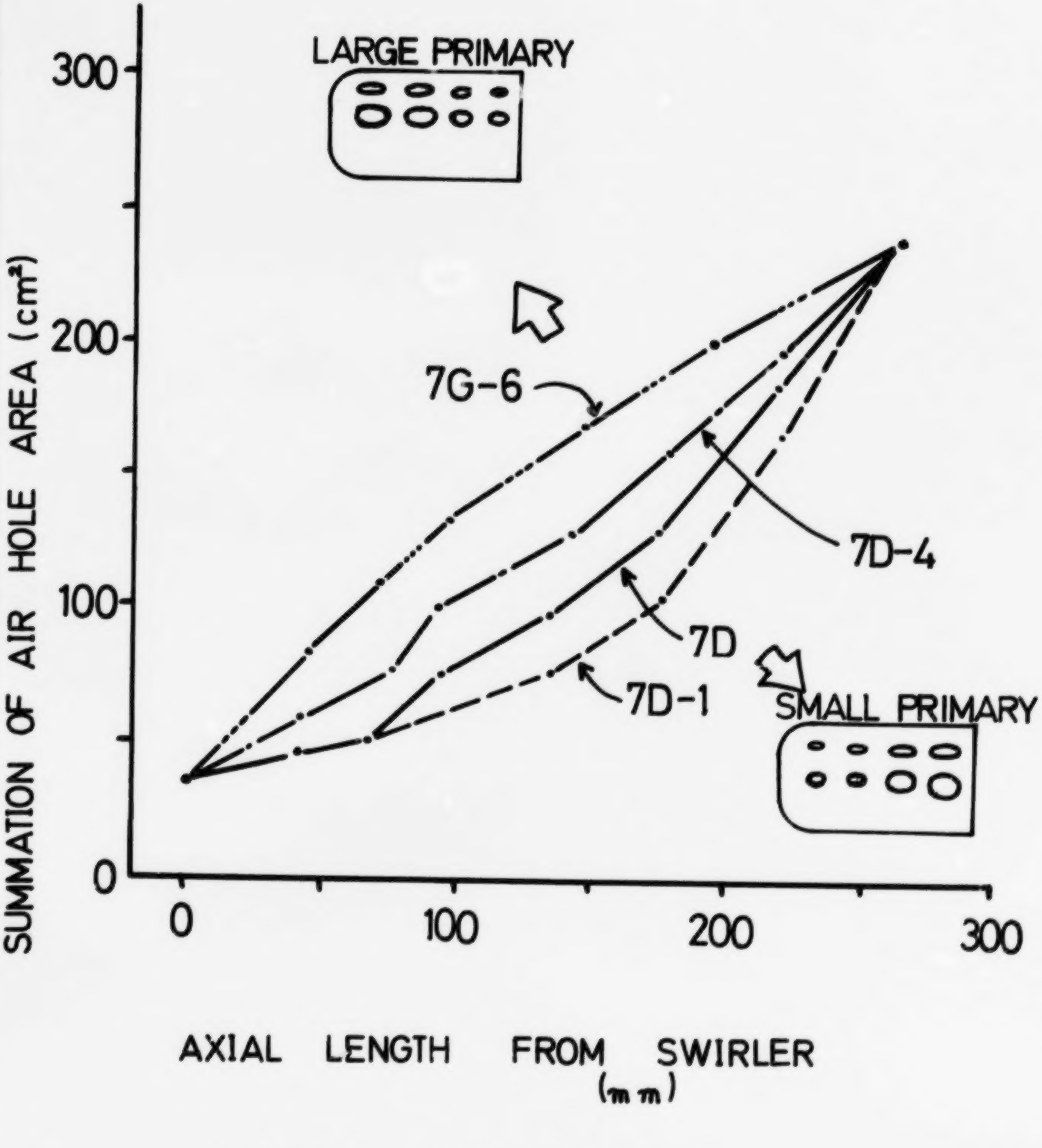


Fig. 12



LINER CONFIGULATION

Fig. 13

CO EMISSION

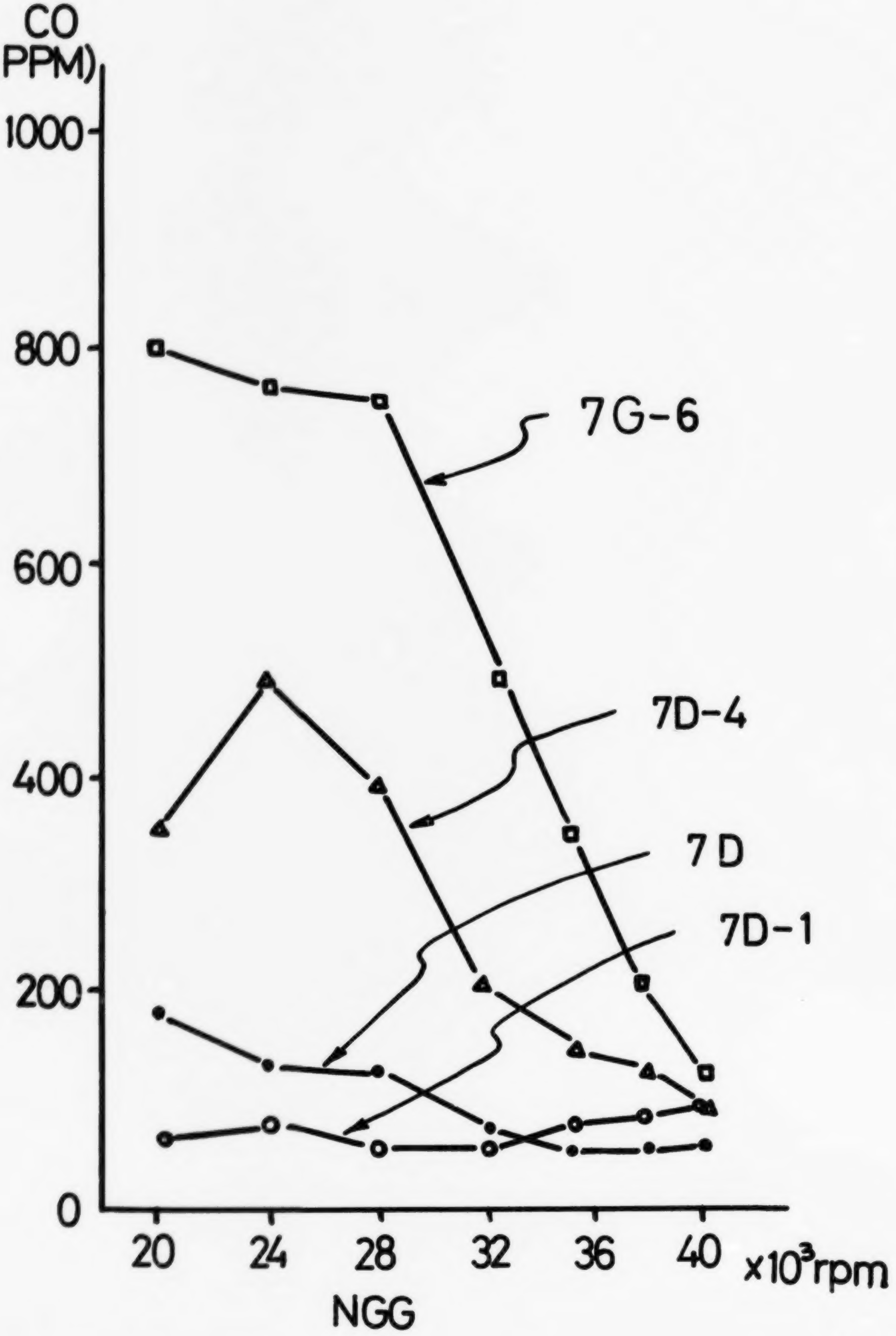


Fig. 14

UHC EMISSION

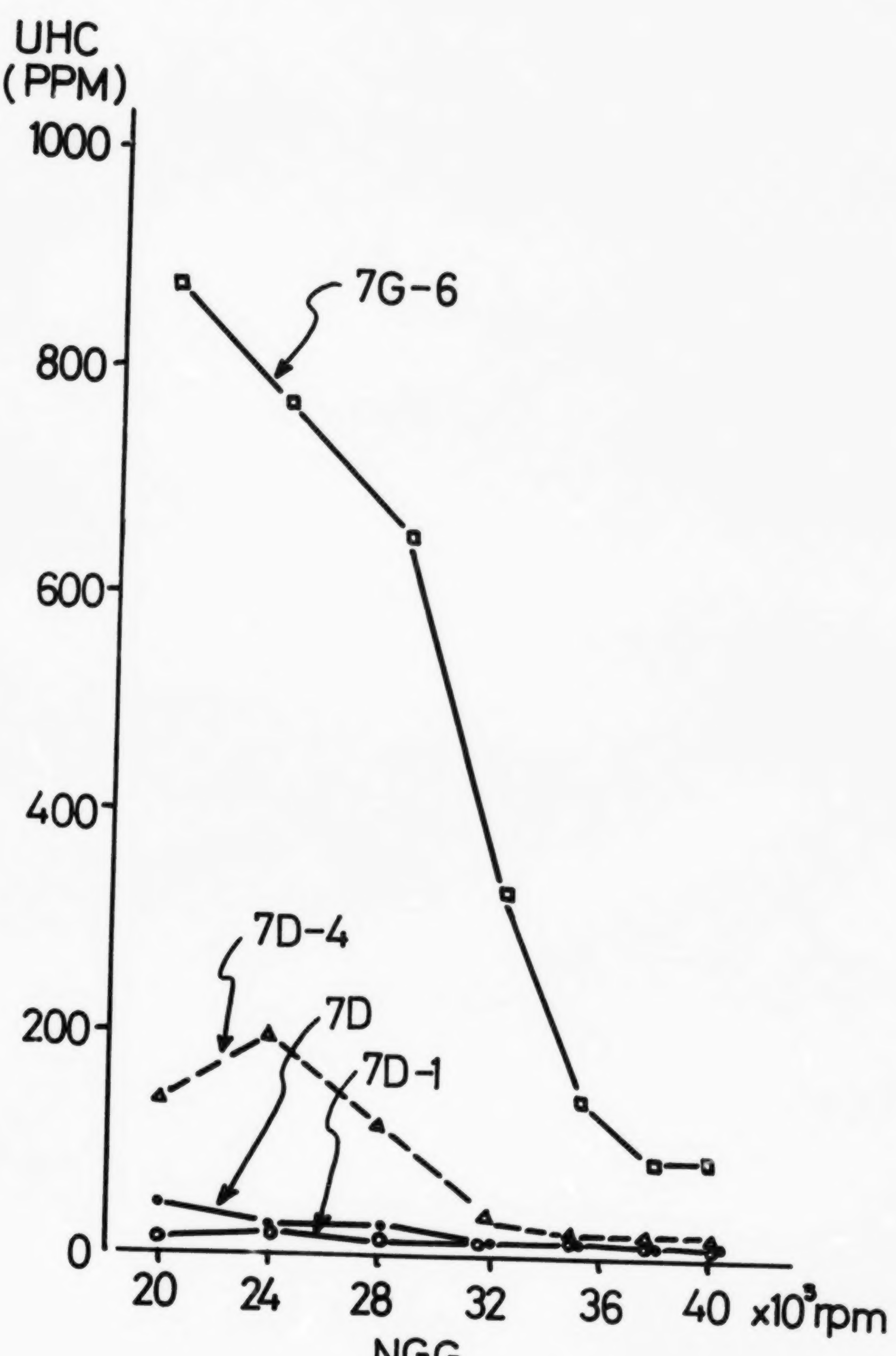


Fig. 15

NOx EMISSION

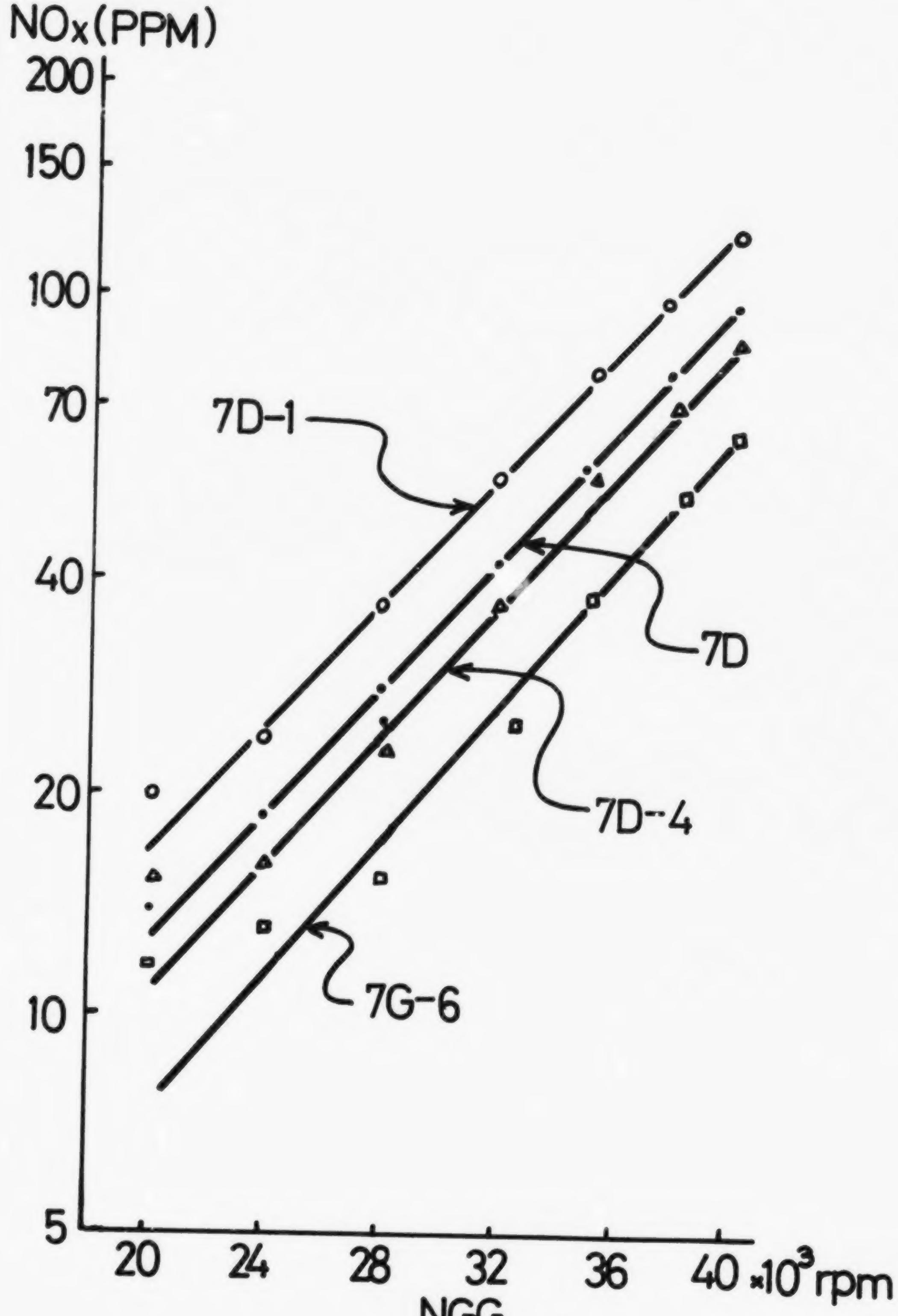


Fig. 16

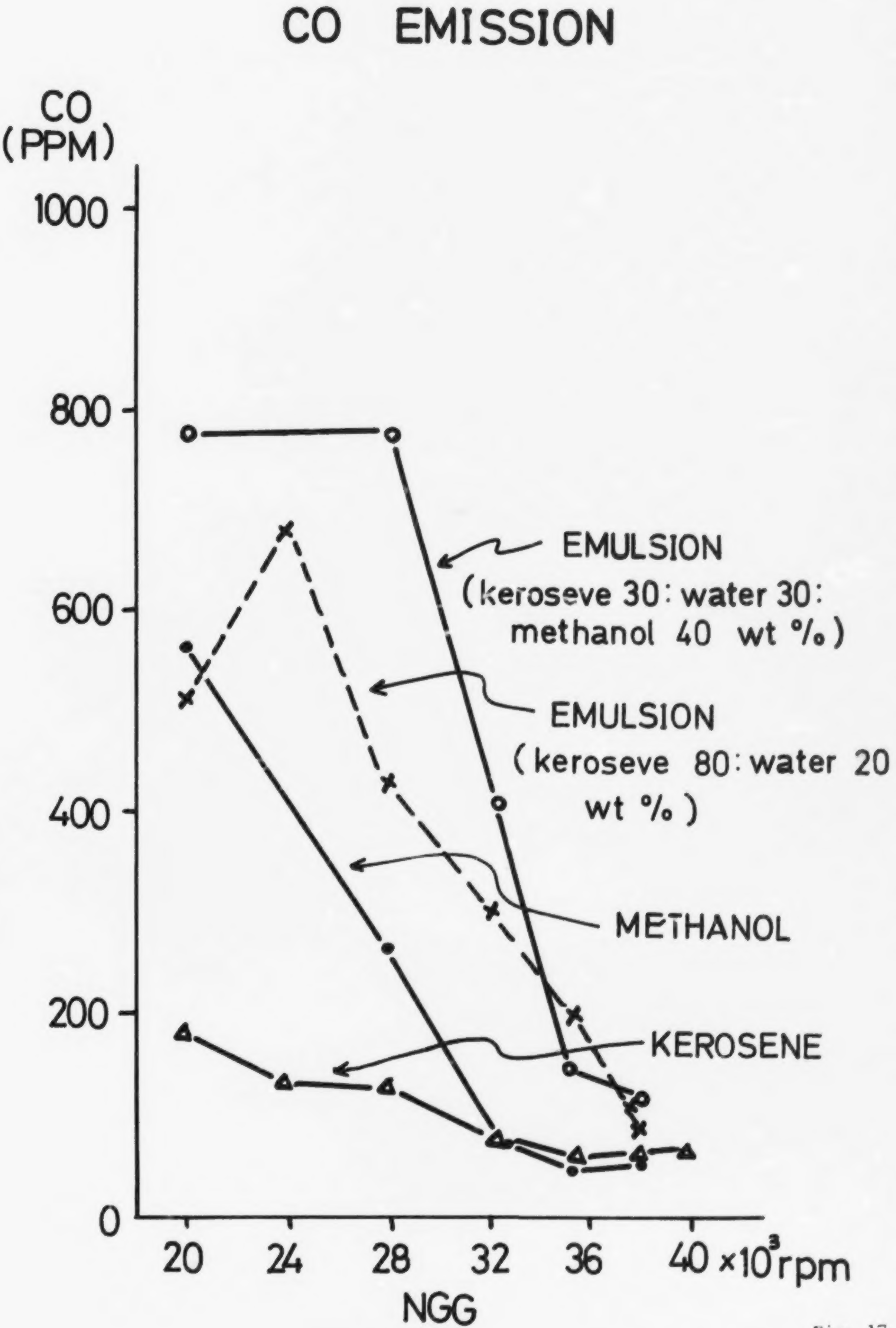
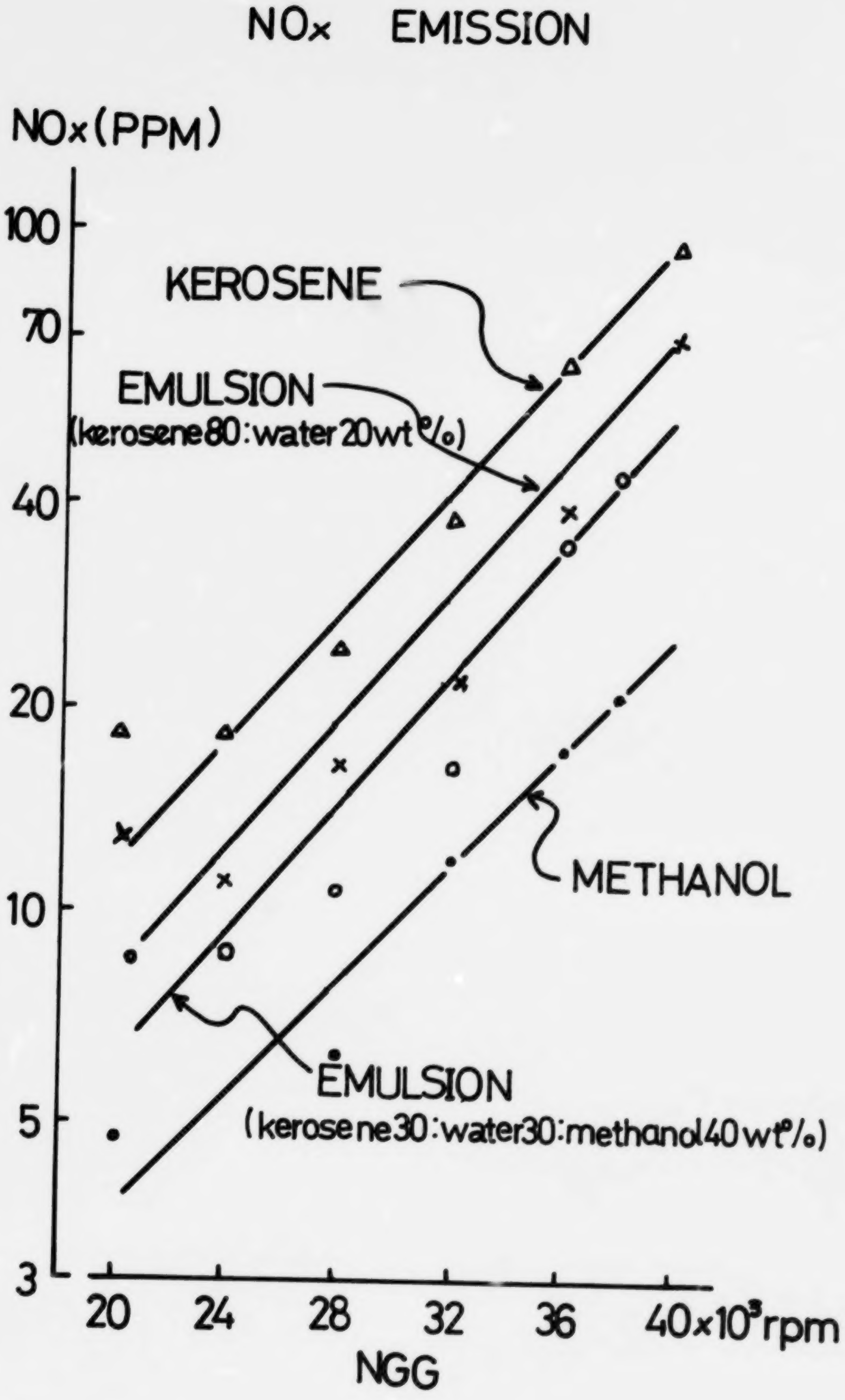

CO EMISSION
CO (PPM)
1000
800
600
400
200
0
20
24
28
32
36
40 ×10³rpm
NGG
EMULSION (keroseve 30: water 30: methanol 40 wt %)
EMULSION (keroseve 80: water 20 wt %)
METHANOL
KEROSENE

Fig. 17



NOx EMISSION
NOx (PPM)
100
70
40
20
10
5
3
20
24
28
32
36
40×10³rpm
NGG
KEROSENE
EMULSION
(kerosene 80 : water 20 wt %)
METHANOL
EMULSION
(kerosene 30 : water 30 : methanol 40 wt %)

Fig. 19

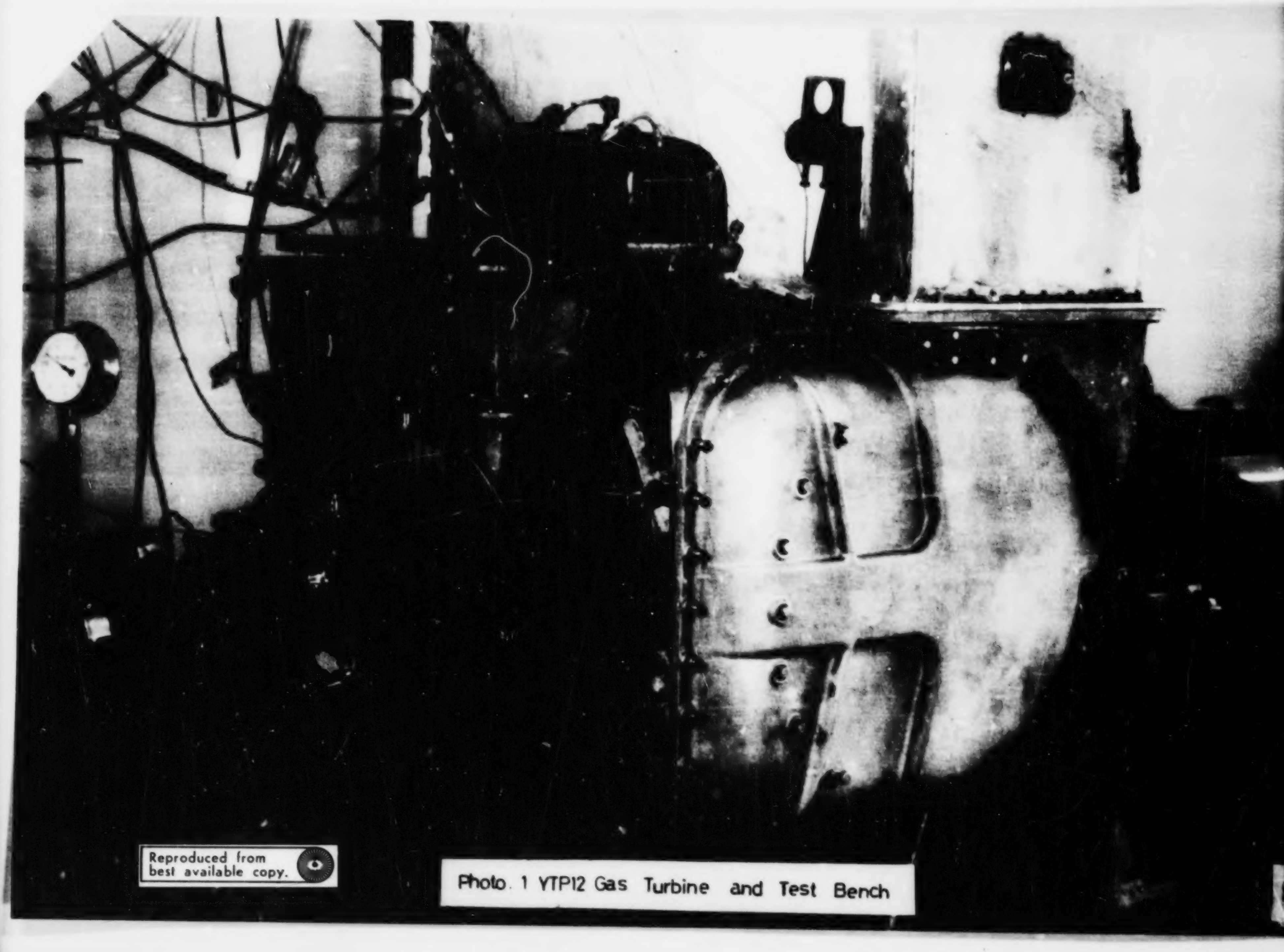


Photo. 1 YTP12 Gas Turbine and Test Bench

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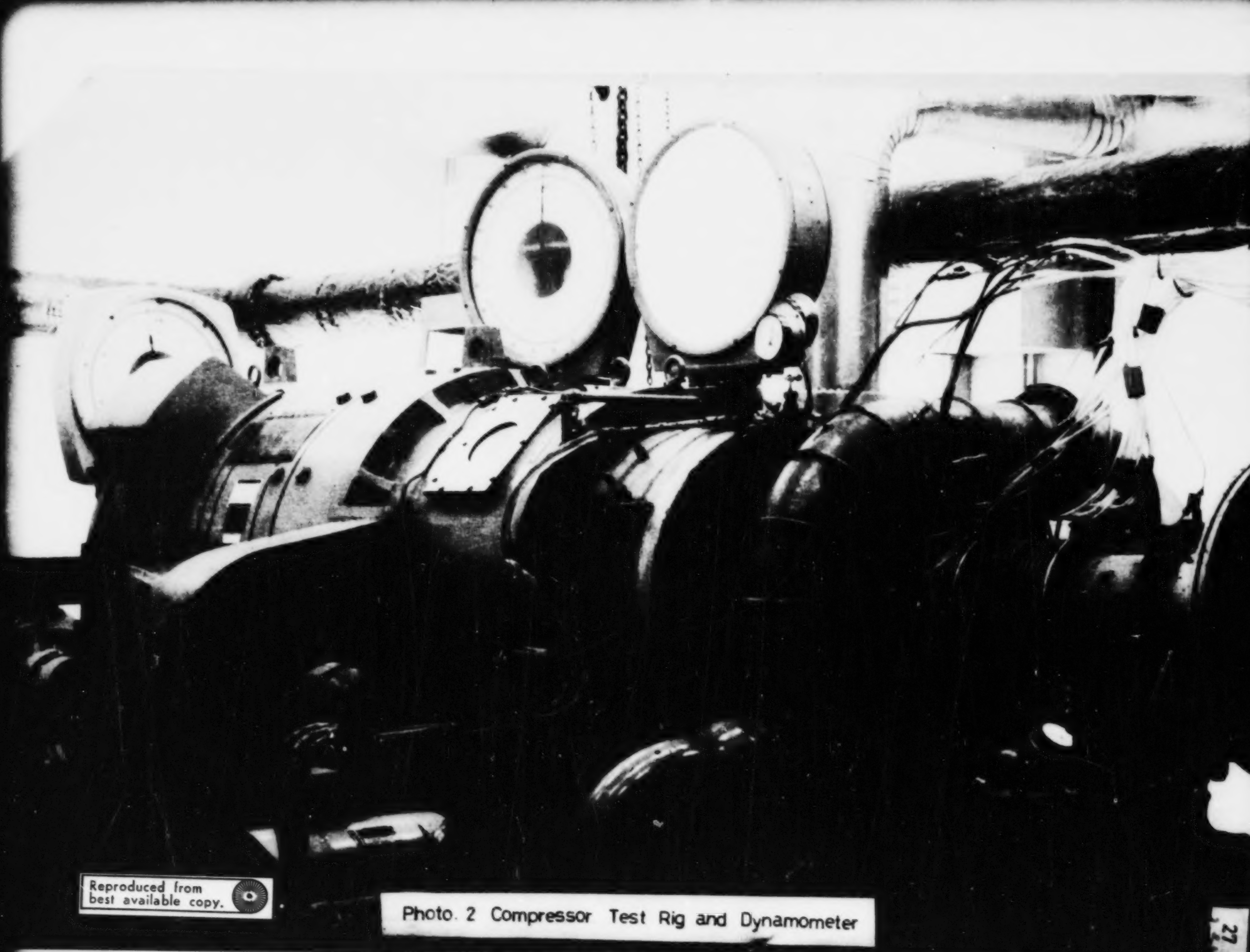

Photo. 2 Compressor Test Rig and Dynamometer

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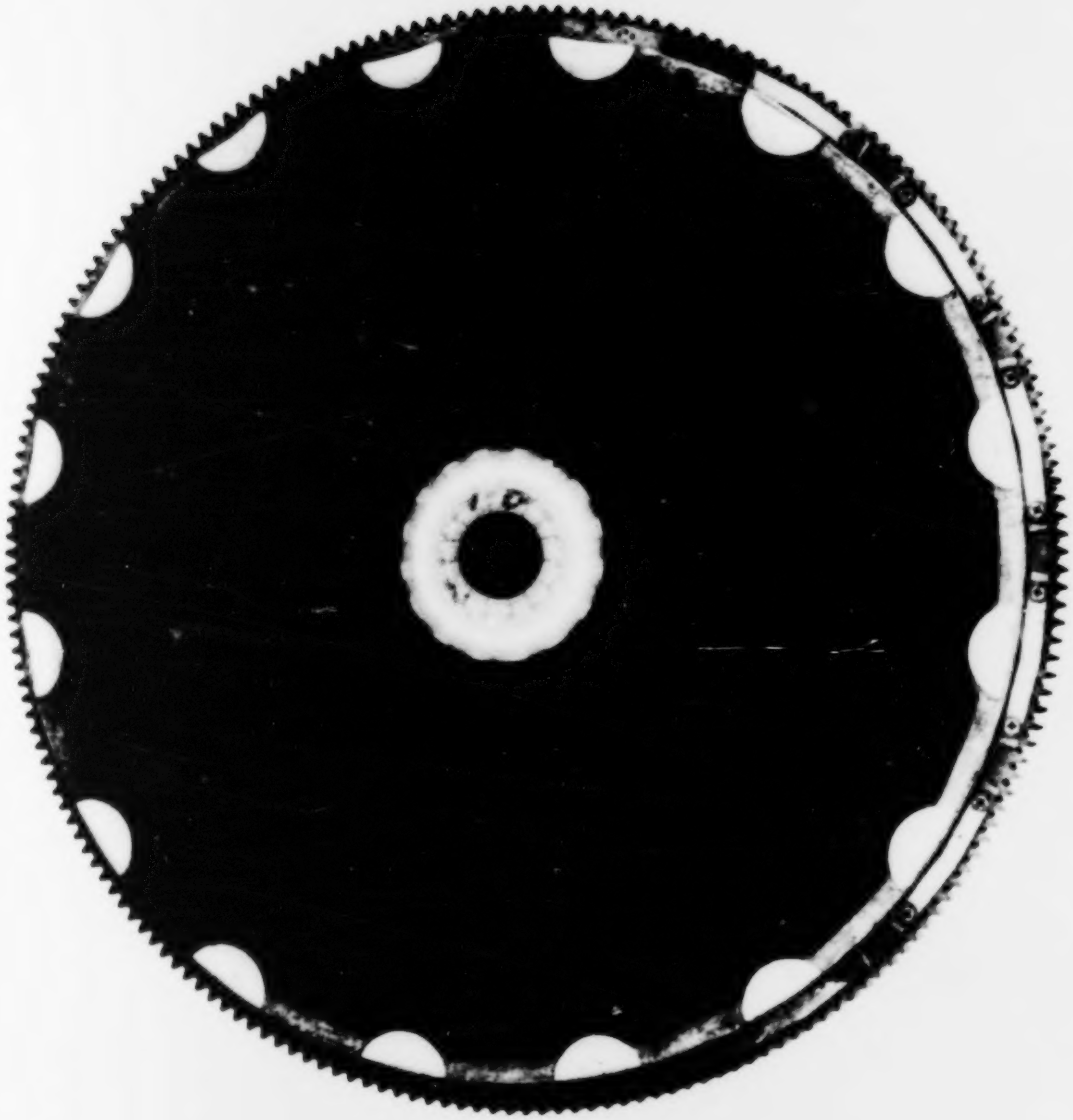


Photo. 3 Ceramic Core

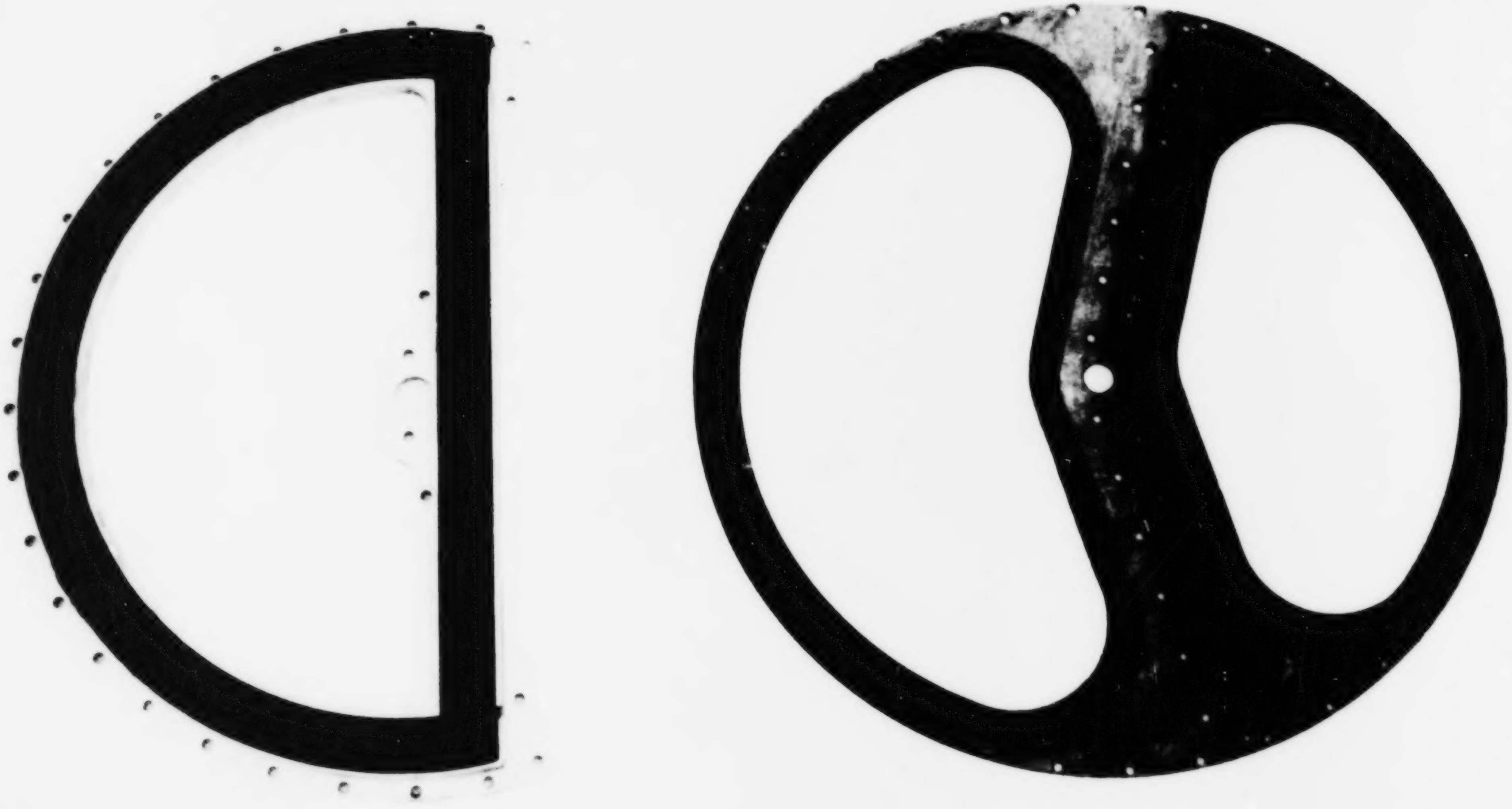


Photo. 4 Bellows Seal (R.H.) and New Seal (L.H.)

Photo. 5 Combustor Liner

CERAMIC MATERIALS AND COMPONENTS FOR SMALL AUTOMOTIVE GAS TURBINE ENGINES-TECHNOLOGY ASSESSMENT

A. E. GORUM, J. J. BURKE, E. M. LENOE, AND R. N. KATZ

Army Materials & Mechanics Research Center
Watertown, Massachusetts 02172

This paper discusses recent developments in ceramic materials and ceramic gas turbine engine components. The significant additional research and development efforts required for making the transition from a 200-hour technology demonstration to an actual 3000-hour engine life and/or component reliability demonstration are discussed. Accordingly, this assessment includes discussion of the major problems, required service goals, status of component development, state of materials and industrial capability, and major gaps in technology which must be considered before embarking on a large-scale engine development program.

On présente une evaluation de l'etat courant du développement des matériaux céramiques pour servir dans une turbine, et on fait une résumé des domaines dans lequelles plus d'efforts significatives des recherches et du developpement s'exigent pour faire la transition d'une démonstration de 200 heures d'opíration, possible actuellenent jusquà une démonstration de 3000 heures d'opíration d'une turbine vrai.

Fortschritte in der Entwicklung von keramischen Materialien zur Verwendung in Gas-Turbinen werden diskutiert. Das letzte Ergebnis des gegenwärtigen US-Hochtemperatur-Gas-Turbinen-Programmes wird eine 200-Stunden-Demonstration einer experimentiellen Turbine sein. Um den Übergang von einer 200-Stunden-Technologie zu einer realistischen 3000-Stunden-Testdemonstration zu verwirklichen, wird jedoch wesentliche weiters Forschungs- und Entwicklungsarbeit nonwendig sein. Auf der Grundlage dieser Übersicht werden Forschungs- und Entwicklungsgebiete der Keramik aufgezeigt, die in den nachsten 3-5 Jahren Aufmerksamkeit benötigen werden.

I. INTRODUCTION

Ceramic materials make higher turbine inlet temperatures, higher component service temperatures and more efficient heat exchangers possible; coupled with lower materials cost, lessened dependence on critical raw materials (such as nickel), and much improved fuel economy. This, together with the availability of greatly improved thermal shock-resistant structural ceramics, led to the design and testing of ceramic hot flow path components, starting about five years ago at Ford Motor Company[1]. This work, as well as work on ceramic vanes for large industrial gas turbines at the Westinghouse Electric Corporation, was significantly accelerated by Advanced Research Project Agency (ARPA) funding. The objective of this ARPA five-year "Brittle Materials Design" Program is the demonstration of ceramic hot flow path components, operating uncooled for 200 hours of typical duty cycle operation in both vehicular and power generating turbines. The Army Materials and Mechanics Research Center (AMMRC) was chosen to monitor the program. At the midpoint of the ARPA program some principal achievements are as follows:

PROGRESS TO DATE ON ARPA VEHICULAR CERAMIC GAS TURBINE (FORD)

- Nose Cone, first stage stator and shrouds successfully passed 50-hour engine testing at 1930F
- Combustor tested 50 hours, six hours at 2500F turbine inlet temperature
- Cold spin test of ceramic rotor to 55,070 rpm

PROGRESS TO DATE ON ARPA STATIONARY CERAMIC GAS TURBINE (WESTINGHOUSE)

- Vane assemblies successfully tested at 2200F
- Constructed 2500F rig for vane component testing

It appears, based on the results of the work cited above, that a small all-ceramic hot flow path automotive gas turbine is both technically and economically feasible. However, it is equally apparent that many engineering problems remain to be addressed. Long-duration testing of a statistically meaningful number of components and engines will be required before design reliability and confidence can be established for such engines. It is also apparent that the most effective technology transfer from the ARPA and related programs is to be effected via a planned entry into the ceramic turbine area during, rather than at the end of, the ARPA Program.

As the current ARPA Program is an iterative systems approach to the development of a ceramic gas turbine engine, several major activities will be phasing out in an orderly manner as the time for the major 200-hour demonstration draws near. For example, all demonstration hardware must be fabricated, inspected, qualified, re-inspected, possibly proof-tested, and then run in the demonstration engine. The time to complete this cycle will eventually preclude the entry of new materials into the program and this will probably occur late in 1975. Similar phaseouts will occur for the other program elements. Finally all that remains will be the 200-hour demonstration. Unless interested agencies initiate research programs in materials, non-destructive evaluation, proof-testing, and design capability as these areas phase out of the ARPA Program, the momentum and cohesion of the technology neccessary to make the transition from the 200-hour technology demonstration to a 3000- or 4000-hour true engine demonstration will be lost.

Therefore, EPA/AAPS has tasked AMMRC to prepare a survey to elucidate those technology gaps which currently exist and will continue to exist at the termination of the ARPA Program and to provide guidance for making the transition from a 200-hour technology demonstration to a true long-term engine demonstration. What follows is a brief summary of that survey including the current state-of-the-art in ceramic materials and engine components development together with our opinion of some of the remaining gaps in basic knowledge and technology.

II. MAJOR TECHNOLOGY PACING PROBLEMS AND RESEARCH REQUIREMENTS

The ARPA Program originally planned to utilize off-the-shelf structural ceramics. Yet during these few years, remarkable improvements in several types of candidate ceramic materials were achieved with regard to high-temperarure strength steady state creep, creep rupture, and dimensional stability under severe combustion environments. New production techniques were also developed for ceramic nitrides, carbides, and regenerator core materials, which promise practical, large-volume component manufacturing capability. As mentioned in the introductory passages, current engine programs have limited goals, and it appears that the existing materials technology is adequate to meet a 200-hour demonstration.

On the other hand, existing high-temperature structural ceramics have not been subjected to long-term characterization. A totally successful ARPA program demonstration will have given design confidence for a time which amounts to only 5 percent of the expected life of an actual engine. Presently there is no significant property data base beyond 150-200 hours at temperature for materials of interest. Thus, the first step leading to a true engine demonstration program would be to obtain mechanical, chemical, thermal, and physical properties data, dimentional stability, and component test life data for durations of thousands of hours of simulated service exposure. These studies would serve to ferret out deficiencies in present candidate materials.

To maximize the full potential for future ceramic gas turbine application, it is necessary to simultaneously pursue additional materials and processing research aimed not only at improving current ceramics, but to initiate long-term programs to develop "new" materials.

Examination of available engineering methodology also suggests that it is necessary to seek improved stress analysis techniques emphasizing probability-based methods, to continue studies of fracture, fatigue, creep and life prediction, to assess potential advances in nondestructive evaluation and proof testing, and to develop additional high-temperature instrumentation and deformation measurement procedures.

Ultimately, the feasibility of mass-producing ceramic automotive gas turbine engines depends upon the development of cost-effective regenerators and rotors. If materials and fabrication processes capable of producing satisfactory turbine rotors can be developed, the production of the stationary components (stators, shrouds, combustors, etc.) becomes a relatively simple engineering problem, capable of straightforward solution. Acceptable costs and acceptable durability of ceramic regenerators must also be demonstrated for automotive ceramic gas turbines to be viable.

From fuel economy and engine size considerations there is a clear advantage to having a turbine inlet temperature (TIT) of at least 2500F, although gains can still be achieved at lower TIT's. Even though ceramic combustor technology to yield 2500F TIT is in varying states of development at various engine manufacturers, it would be desirable to have a ceramic combustor demonstrator program to demonstrate low ceramic emissions combustion at 2500F TIT.

It is also evident that manufacturing methods and technology for the supply of high-quality ceramic components in sufficient quantity for large engine development programs must be developed.

Major technology problems have been considered in a general way, and now it is appropriate to discuss specific accomplishments and required research.

1. MATERIALS

The past three years have seen tremendous progress in materials science and engineering with respect to turbine ceramics; silicon nitride (Si_3N_4), silicon carbide (SiC), "SiAlON" (silicon aluminum oxynitrides), lithium aluminum silicates (LAS), and magnesium aluminum silicates (MAS). Silicon nitride, SiC, and LAS are currently being evaluated in component form in the ARPA Program. During the initiation of the ARPA Program, limitations in the behavior of these "off-the-shelf" materials with respect to properties such as creep, necessitated accelerated materials and fabrication research and development. Silicon nitride has been the prime beneficiary of this materials improvement to date. The dramatic improvements in high-temperature bend strength (Figure 1) and creep properties (Figures 2, 3) are indicative of the rate of materials property improvements to be anticipated in the four other turbine ceramics mentioned above. Figure 4 reveals the potential improved creep behavior of SiAlON compared to silicon nitride[2].

The key to a successful and rapid materials improvement program is knowledge of the basic problems. Obviously, solutions to basic problems must be formulated in terms of goals set by realistic designs. Currently, the most important goals are as follows:

- Hot Pressed Silicon Nitride and Carbide - Attain a flexural strength of 150,000 psi (MOR) for temperatures ranging to 2500F, while maintaining good creep and corrosion resistance.

- Reaction Bonded Silicon Nitride - Attain a strength of 60,000 psi (MOR) for temperatures up to 2500F while maintaining good creep resistance.

- "SiAlON's" - Develop a data base on well characterized materials.

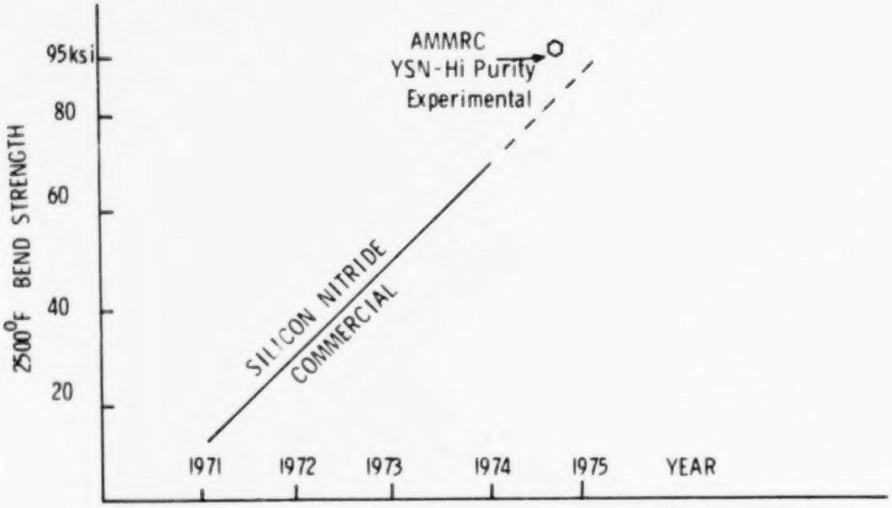


Figure 1. Flexural Strength of Hot Pressed Silicon Nitride

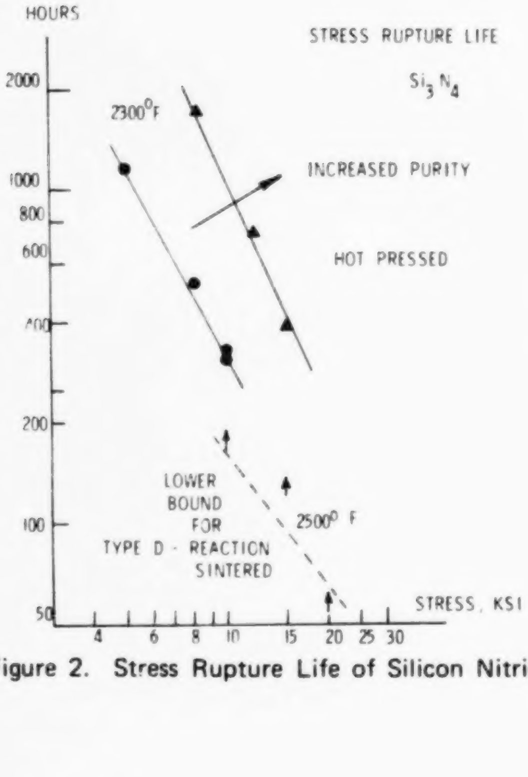


Figure 2. Stress Rupture Life of Silicon Nitride

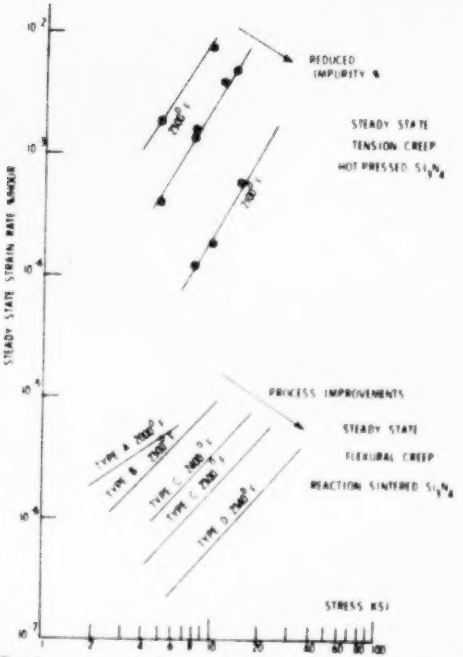


Figure 3. Improved Creep Behavior of Silicon Nitride

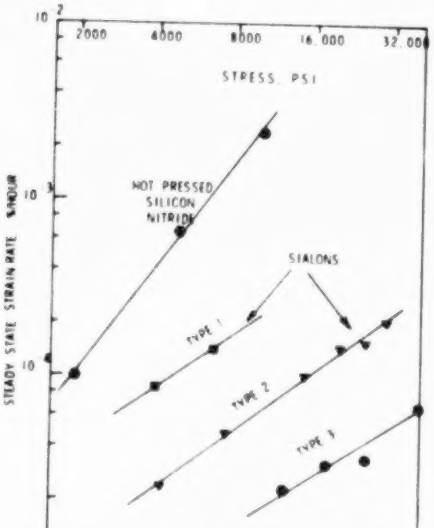


Figure 4. Creep of Silicon Nitride & Sialon. Reference [2]

- LAS - Develop Na and S hot-corrosion resistance and 10,000 psi (MOR).

- MAS - Develop Na and S hot-corrosion resistance and 10,000 psi (MOR).

- All Materials - Develop data on the stability of all critical properties for 4000-hour life over 20,000 thermal cycles in a combustion gas environment.

At the present level of effort it is very likely that these goals will be attained for hot-pressed and reaction-bonded Si_3N_4, LAS and MAS materials over the next two-three years. It is likely that silicon carbide will follow Si_3N_4 development by about one year and "SiAlON's" by about two years.

Turning from the area of materials development to materials supply, the situation can be characterized by one word - insufficiency. At the present time, there is insufficient materials and materials fabrication capacity in the turbine ceramics area for a major engine demonstration program, involving hundreds or even thousands of components such as stators and rotors. Numerous ceramic companies possess the materials and fabrication knowhow but will not make substantial capital commitments until the market situation matures. Thus an orderly and predictable development of a market will be required to assure adequate materials availability.

2. COMPONENTS

A ceramic engine operating at a 2500F, TIT, would have approximately maximum component temperatures as indicated in Figure 5. Taking into account

Figure 5. Materials and Processes for Ceramic Components for Ceramic Engine Operating at T.I.T. of 2500 F Uncooled

CERAMIC COMPONENT	MAX PART TEMP °F	MATERIAL					PROCESS									
		I Si_3N_4	II SiC	III SIALON	IV MAS	V LAS	COLD PRESSING	SLIP CASTING	INJ MOLDING	"REFEL" TYPE	HOT PRESSING	CHEM VAP DEP	EXTRUSION	SINTERING	PAPER WRAPPING	GLASS FORMING
1ST STAGE STATOR	2400	✓	✓	✓				Ib IIb	Ib IIb	IIb				IIb IIIc		
2ND STAGE STATOR	2100	✓	✓	✓				Ib IIb	Ib IIb	IIb				IIb IIIc		
1ST STAGE ROTOR	2300	✓	✓	✓				Ib IIb	Ib*		Ib† d‡	IIc		IIb IIIc		
2ND STAGE ROTOR	2000	✓	✓	✓				Ib IIb	Ib*		Ib† d‡	IIc		IIb IIIc		
1ST STAGE SHROUD	2300	✓	✓	✓			Ib	Ib IIb		IIb	Ib			IIb IIIb		
2ND STAGE SHROUD	2000	✓	✓	✓			Ib	Ib IIb		IIb	Ib			IIb IIIb		
INLET NOSE CONE	2500	✓	✓	✓					Ib IIb					IIb IIIc		
COMBUSTOR	2500		✓	✓						IIa			IIb	IIb IIIc		
REGENERATORS	1800	✓		✓	✓	✓							IVb Vb		Ib IIIc Va	IVb Vb

a = Currently in Hardware Demonstration at Temp
b = 1-3 Years Hence
c = 3-5 Years Hence
d = Technically Feasible but Economically Unattractive

*Hub only for Multi-Density
†Monolithic
‡Blades only for Multi-Density

Status as of 15 July 1974

these temperatures, mechanical properties requirements, and the current fabrication technology, materials and fabrication process choices are indicated in Figure 5. For example, the figure indicates that "Refel" type, extruded, or sintered SiC as well as SiAlON's are potential combustor materials, with "Refel" type SiC already being tested at 2500F and SiAlON being the furthest from component demonstration. During the ARPA Program progress in component design has led to increased life. For example, design improvements (with materials properties held constant) have led to a 60-fold increase in maximum part lifetime over a 2 1/2-year period (Figure 6).

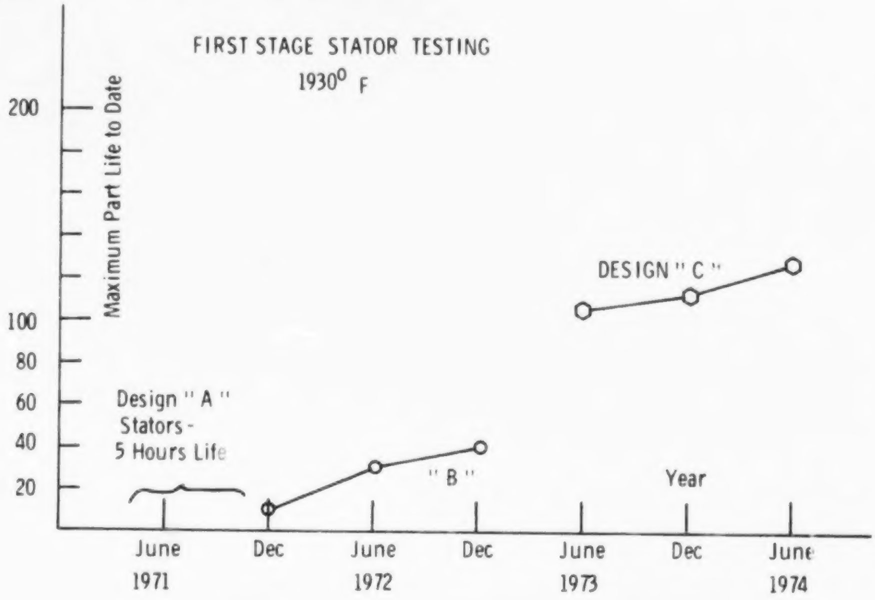


Figure 6. Improvement in Maximum Part Life

At the present time, indications are that the stationary hot flow path components (stators, diffusors, combustors and shrouds) are within the range of straightforward engineering development for attaining the performance required in a small vehicular engine. The coupling of current designs with known improved materials should produce parts capable of 3000 hours at a 2500F maximum TIT.

The situation with respect to rotors and regenerators is less sure. Regenerators or recuperators have been run close to the turbine exit temperatures anticipated for 2500F maximum TIT operation. However, these are costly, of limited availability, and with inadequate properties for long life in corrosive environments.

The situation with rotors is even less certain. No rotor has yet been hot tested. During the ARPA Program ten approaches to an automotive rotor have been tried by Ford and seven discarded as unfeasible. The main approaches under continued development are:

- Hot pressed Si_3N_4 hubs with high density injection molded or slip cast blade rings (multi-density approach)
- Sintered SiC rotors

It should be noted that Ford has cold spun an all-ceramic multi-density Si_3N_4 rotor to 55,070 rpm, and cold spun blades to 61,900 rpm. Japanese researchers have cold spun hot pressed Si_3N_4 blades to 77,000 rpm[3]. Thus, there have been some encouraging results.

It is clear that in the component area the required major thrusts are the following:

- Rotor development.
- Regenerator/recuperator development.
- Durability testing of stationary hot flow path components.

3. LIFE PREDICTION AND RELIABILITY

Ceramic hot flow path component tests have been completed on early design versions and first-generation materials. A severe duty cycle, representative of only a small percentage of the anticipated service load spectrum, has been chosen in order to aid in pinpointing design and materials deficiencies. We have interpreted the early test results using extreme value statistics. Use of these distribution functions is based on the notion that first-generation attempts, which include many manufacturing as well as design and material defects, ought to be better represented by extreme value statistics rather than normal or other distribution functions. A typical set of results for first-stage stators is shown in Figure 7. Note the improvement achieved between Design B and Design C. The earlier "B" design life distributions showed no probability of meeting even a 200-hour goal, where Design C has a small but finite change of the ARPA target. Since that time, significant advances have been made in ceramic hot flow path materials and component processing.

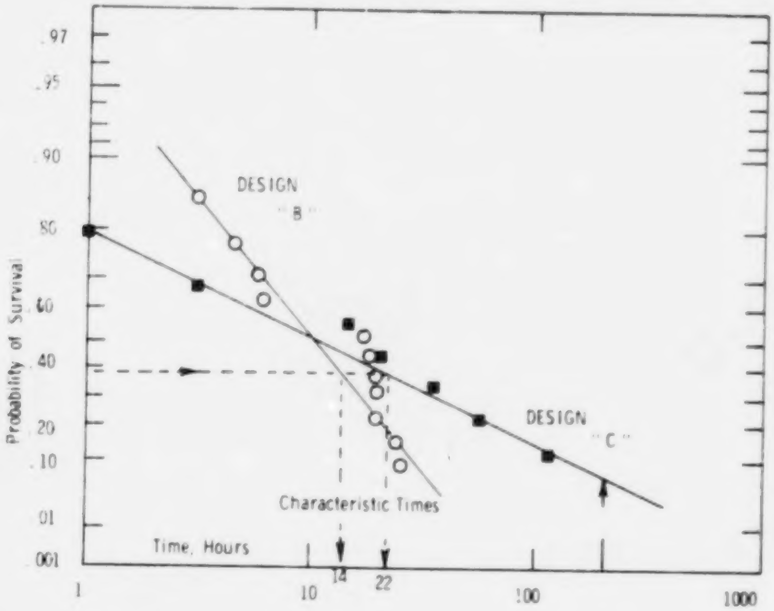
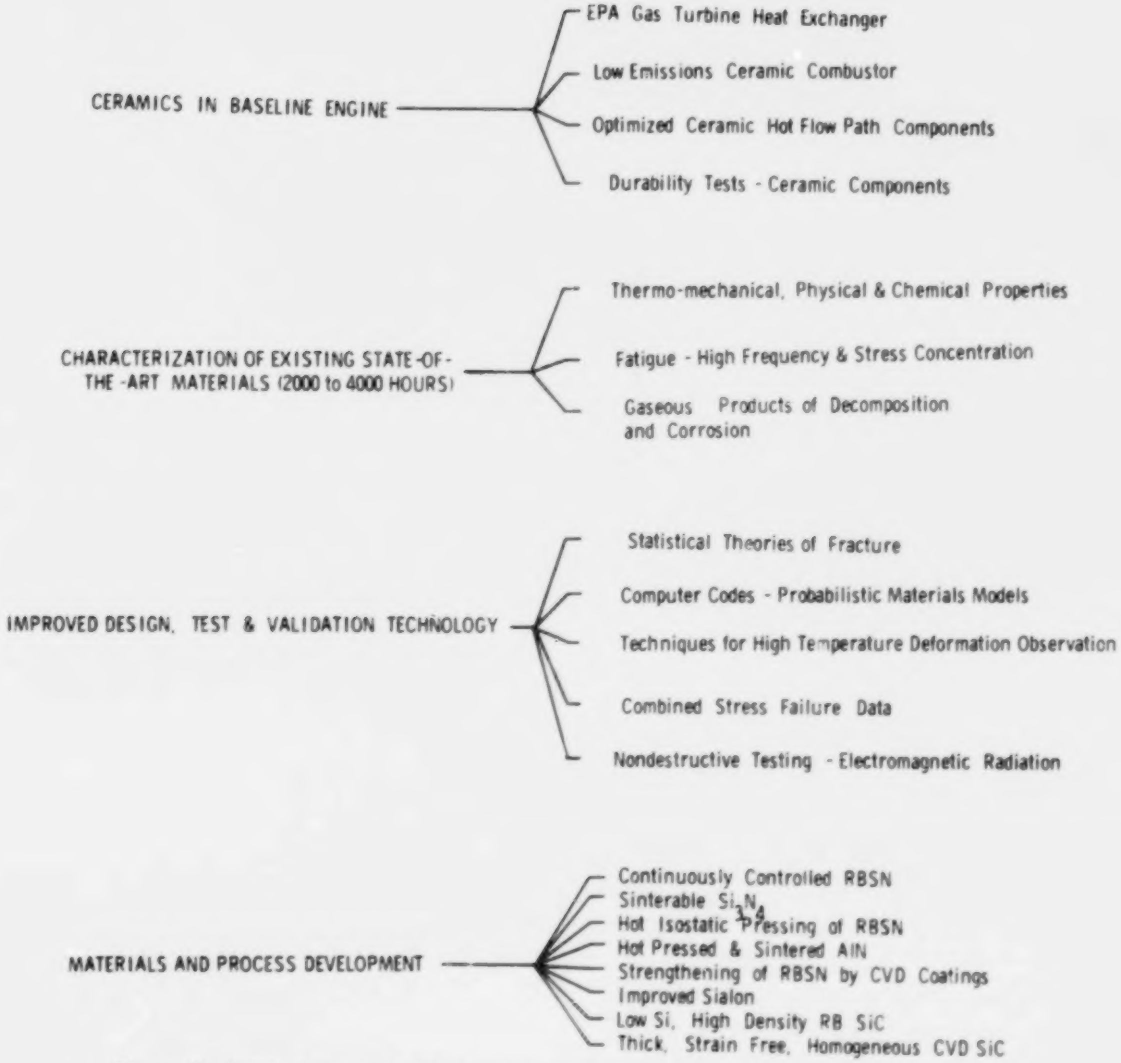


Figure 7. Extreme Value Life Distributions First Stage Stators

SUMMARY OF CRITICAL RESEARCH TASKS



- CERAMICS IN BASELINE ENGINE
  - EPA Gas Turbine Heat Exchanger
  - Low Emissions Ceramic Combustor
  - Optimized Ceramic Hot Flow Path Components
  - Durability Tests - Ceramic Components
- CHARACTERIZATION OF EXISTING STATE-OF-THE-ART MATERIALS (2000 to 4000 HOURS)
  - Thermo-mechanical, Physical & Chemical Properties
  - Fatigue - High Frequency & Stress Concentration
  - Gaseous Products of Decomposition and Corrosion
- IMPROVED DESIGN, TEST & VALIDATION TECHNOLOGY
  - Statistical Theories of Fracture
  - Computer Codes - Probabilistic Materials Models
  - Techniques for High Temperature Deformation Observation
  - Combined Stress Failure Data
  - Nondestructive Testing - Electromagnetic Radiation
- MATERIALS AND PROCESS DEVELOPMENT
  - Continuously Controlled RBSN
  - Sinterable Si_3N_4
  - Hot Isostatic Pressing of RBSN
  - Hot Pressed & Sintered AlN
  - Strengthening of RBSN by CVD Coatings
  - Improved Sialon
  - Low Si, High Density RB SiC
  - Thick, Strain Free, Homogeneous CVD SiC

Figure 8. Critical Research Task Spiderchart for a Small Ceramic Engine

At the onset of the ARPA Program, no fracture mechanics data was available for the majority of candidate materials. Furthermore, there was little understanding of basic creep and fatigue mechanisms. Since that time a great deal of progress has been made in determining creep mechanisms in hot-pressed, reaction-sintered and slip-cast Si_3N_4. A variety of fracture mechanics experiments have been completed and slow crack growth data is now available for the most important turbine ceramics. Several methods of life prediction[4] have been developed, based on strength-probability and time-to-fracture concepts[5]. Comparisons of existing component tests lives to such predictions suggest that the engineering methodology is conservative, thereby providing an essential tool for the design engineer. Since the technique is conservative, it is useful to pursue further improvements in order to more efficiently utilize ceramic components. Finally, it is true that further study is required to develop reliability prediction techniques for spectrum loading.

CONCLUSIONS

Subsequent to a thorough review of current ceramic research, as well as that planned for the next few years by various United States Government agencies and industrial concerns, the critical research and development areas which must be addressed were identified. These studies are identified in the Schematic (Figure 8) The twenty tasks fall into the several categories: (1) Potential for Ceramics Utilization in the EPA/AAPS Baseline Engine, (2) Long-Term Characterization, (3) Design Test, and Evaluation, and (4) Materials and Process Development. These projects represent our best estimate of the studies required to achieve an orderly transition from demonstrated 200-hour lives to the thousands of hours necessary for a practical gas turbine engine. The indicated research areas are the minimum critical studies which must be undertaken as of now if the present rate of progress is to continue.

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The ARPA/Ford All Ceramic Turbine Development Program

A. F. MC LEAN
Ford Motor Company
P. O. Box 2053

Dearborn, Michigan 48121

This paper presents progress on the ARPA/Ford program to develop materials, fabrication processes and designs to apply ceramics to a vehicular, high temperature gas turbine engine. The reasons for investigating ceramics are reviewed. Developmental progress on both rotating and stationary, critical ceramic flow path components is discussed and current status is reported.

INTRODUCTION

It has been reported elsewhere(1) that a program is under way to develop materials, fabrication processes and designs to apply ceramics to a vehicular, high temperature gas turbine engine. The potential benefits in using ceramics (2) are improved engine efficiency and size by operating at higher turbine inlet temperature, and lower cost by using materials more readily available and abundant than conventional turbine superalloys. The objective of this program is to be able to raise the turbine inlet temperature of the "ceramic engine" to 1370°C compared with 980-1035°C for today's "uncooled-metal engine". This would result in a doubling of horsepower for the same engine size and a 20-30% improvement in efficiency at full power; even greater efficiency improvements would be realized at part power, which is especially significant for automotive applications.

A high temperature turbine engine,(3) which was specially designed to develop ceramic components, is being used in this program and is shown in Figure 1 with the combustor removed and ceramic nose cone being removed.

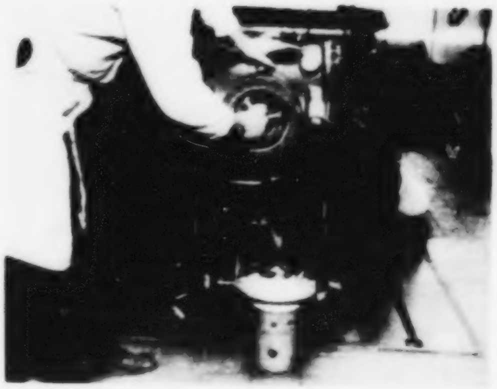

Fig. 1 "Ceramic, High Temperature Turbine Engine"

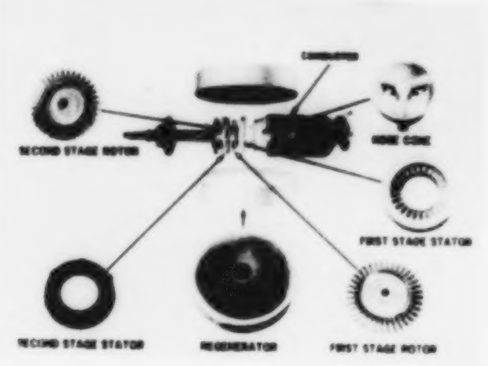

Fig. 2 "Ceramic Hot Flow Path Components"

The critical, high temperature, ceramic flow path components within the engine are shown in Figure 2 and include the combustor, turbine inlet nose cone, 1st and 2nd stage turbine stators, and 1st and 2nd stage turbine rotors. This paper will report progress on the development of each of these components.

CERAMIC COMBUSTOR

The combustor is essentially a tubular or "can-type" structure which houses the combustion process; it is located upstream of the turbine inlet nose cone, as shown in Figure 2. To date, ceramics have been investigated for the tubular portion of the combustor while retaining a specially designed attaching metal dome.

Several combustor tubes have been made of slip cast reaction sintered silicon nitride;(4) upon testing, these were shown to result in severe cracking. A number of combustor tubes were made from Norton's CS-101, CS-201 and CS-411 materials; these are grades of "Crystar" silicon carbide.(5) At least one failure occurred in each of the combustors tested. The most successful combustor material to be tested to date is reaction bonded silicon carbide (Refel)(6) from England's Atomic Energy Establishment.

A "Refel" silicon carbide combustor was tested in a combustor test rig as shown in Figure 3, which simulates the operating conditions experienced in an engine. Viewing ports have been designed into the rig to provide for visual observation of the interior and exterior of the combustor during actual operation. The combustor tube has been successfully tested over a cycle comprising 40 cold starts and 150 hours of operation up to turbine inlet temperatures of 1370°C.

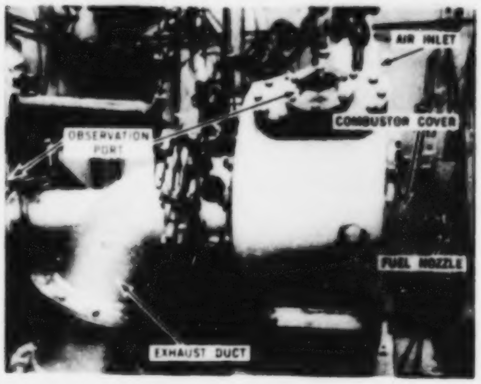

Fig. 3 "Combustor Test Rig"

A picture of the "Refel" silicon carbide combustor after testing is shown in Figure 4. From the successful results of this test, reaction bonded silicon carbide is considered the leading candidate for use in ceramic combustors. Further testing of a larger sample will be necessary to substantiate this conclusion.

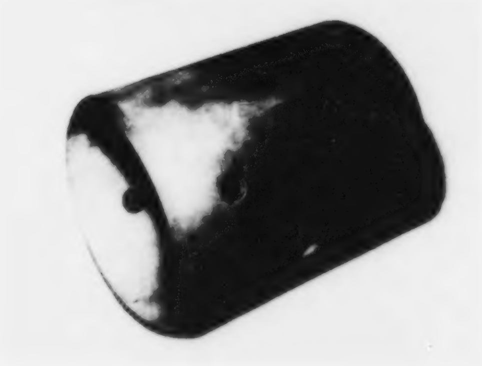

Fig. 4 "Refel Silicon Carbide Combustor"

CERAMIC NOSE CONE

The nose cone is a high temperature structure which is located between the combustor and the turbine stages; its purpose is to distribute the hot gasses discharging from the combustor into the turbine inlet annulus. The nose cone is made of reaction sintered silicon nitride and is made in one piece by injection molding.(7)

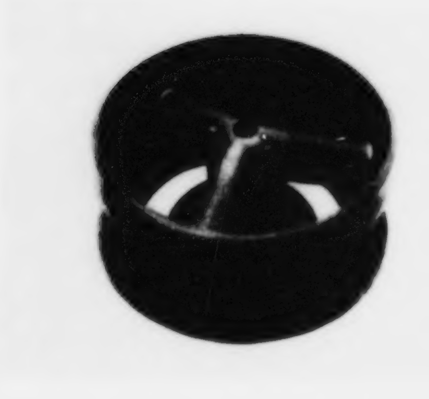

Fig. 5 "Design 'A' Si_3N_4 Nose Cone, as Molded"

Figure 5 shows an early Design "A" nose cone configuration as injection molded. During engine testing of this type of nose cone, outer shroud cracks occurred which, although non-catastrophic for the extent of testing conducted, could have caused a piece to break away over longer periods of testing. The temperature gradient and associated thermal stress across the wide flange at the downstream face of the nose cone was thought to have caused this cracking problem. Since the purpose of the flange was only to locate the nose cone, the design was modified to scallop the flange, thereby reducing thermal stresses while retaining location capability. Axial cracking in the nose cone outer shroud still occurred and investigation showed this was caused by different heating and cooling rates of the three struts supporting the inner nose cone. To provide for a small degree of relative expansion of these struts, the outer shroud was cut axially in three places. This configuration with the scalloped flange and three axial slots is designated the Design "C" nose cone.

Another problem was associated with internal flaws in the fabrication of Design "C" nose cones; an example is shown in Figure 6, where the machined scallop in the nose cone flange has exposed a large internal void. It was found that the flaws were mainly caused by uneven cooling shrinkage of the molded part in the tool. Selective heating of the tool to minimize shrinkage differences was shown to produce good quality parts with no internal voids. The actual technique used to assess part quality was X-ray radiography of the green as-molded body.

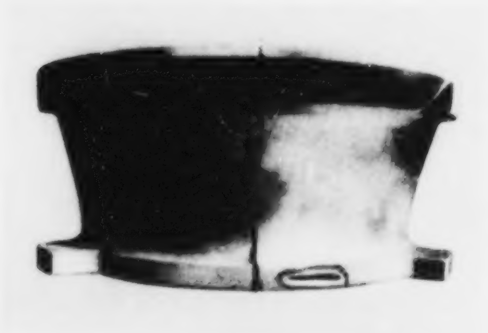

Fig. 6 "Design 'C' Si_3N_4 Nose Cone"

A limited number of Design "C" nose cones have now been engine tested and results show no failures to date. However, further testing of a larger sample will be necessary to establish whether Design "C" has positively resolved all the cracking problems.

CERAMIC TURBINE STATORS

1st Stage Stator. The 1st stage stator is concentric with and axially located between the turbine inlet nose cone and the 1st stage turbine wheel, as shown in Figure 2. As with the nose cone, the 1st stage stator is made of reaction sintered silicon nitride.

Early Design "A" 1st stage stators were made by assembling and bonding individual injection molded blades, as shown in Figure 7. In this design, the shroud surrounding the 1st stage turbine wheel was formed by an extension as part of the stator itself. Engine testing of this design resulted in cracking at the base of the airfoil vane often after only a few thermal shocks. An investigation of this traced the problem to high thermal stresses due to the low mass of the vane relative to the vane base. As a result, the design was modified to Design "B" to separate the turbine shroud and thin-down the U-channel which formed the vane base.

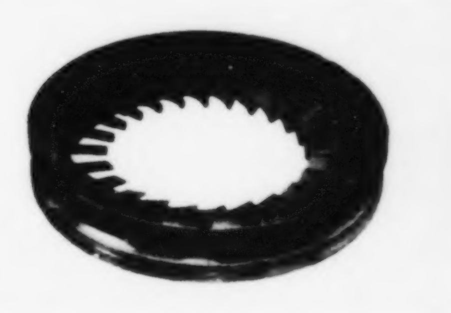

Fig. 7 "Design 'A' Si_3N_4 1st Stage Stator"

Results of engine testing of Design "B" 1st stage stators indicated a solution to the short-time thermal shock cracking problem at the vane base, but revealed a new problem of thermal cracking at the vane mid-span location. This was found to occur under severe transient conditions which created a hot spot at the vane trailing edge. Reducing the vane chord by cutting back the trailing edge proved to offer a solution to this problem and led to Design "C". A segment of a Design "C" stator with reduced chord is shown in Figure 8.

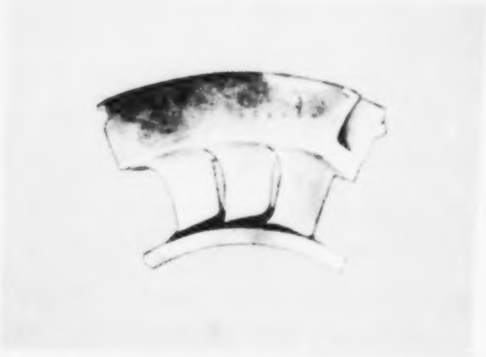

Fig. 8 "Segment of Design 'C' Si_3N_4 1st Stage Stator"

Results of engine testing Design "C" 1st stage stators showed that vane cracking had been eliminated. The remaining problem to be solved was that of cracking of the outer shroud which, though a persistent problem, was noncatastrophic in the engine and had therefore not been given the same emphasis as vane cracking. Although the stresses in the outer shroud of the 1st stage stator were computed to be well within the strength of reaction sintered silicon nitride, it was believed that the bonding of individual blades created notches and associated stress concentrations. Fabrication of the stator in one piece was judged to be a solution to this problem by providing a continuous outer shroud and would additionally greatly reduce fabrication time at the expense of more complex tooling. Accordingly, tooling to make a one-piece injection molded Design "C" 1st stage stator was designed, procured and debugged. Several one-piece stators have been molded, an example being shown in Figure 9. It should be noted that adjacent blade platforms at the inside diameter are separated as with earlier designs by a fine gap to provide for relative expansion of each vane. Engine testing of the first one-piece, 1st stage stator has started and, to date, no cracking of either vanes or outer shroud has occurred.

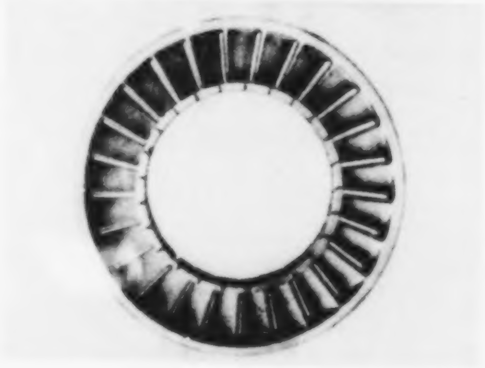

Fig. 9 "One-piece Design 'C' 1st Stage Stator"

2nd Stage Stator. The 2nd stage stator is concentric with and axially located between the 1st stage and 2nd stage turbine wheels, as shown in Figure 2. As with the nose cone and 1st stage stator, the 2nd stage stator is made of reaction sintered silicon nitride.

Early phases of development of the 2nd stage stator essentially paralleled that of the 1st stage. Design "A", made by assembling and bonding individual injection molded vanes, incorporated the 2nd stage turbine wheel shroud. Design "B", on the other hand, separated the turbine shroud and reduced the mass of the blade base. Figure 10 shows a comparison of Designs "A" and "B" for both 1st and 2nd stage stators.

As in the case of the 1st stage stator, outer shroud cracking occurred during engine testing at 1035°C. Fabrication in one piece should solve this problem by eliminating the notch stress concentrations; however, so far this has proved impractical because of blade overlap necessary in the 2nd stage to provide adequate aerodynamic turning. As an alternative, an "inverted channel", Design "B" 2nd stage

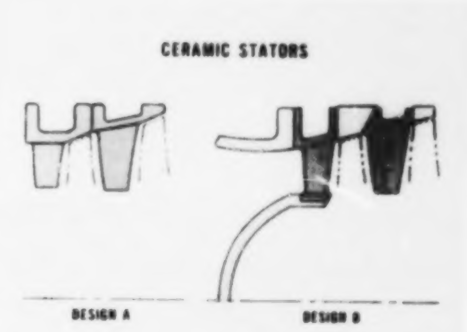

Fig. 10 "Comparison of Design 'A' and 'B' Stators" stator was conceived. In this, as shown in Figure 11, pre-sintered injection molded silicon nitride vanes are bonded into a channel on the inside diameter of a pre-sintered slip cast silicon nitride outer shroud; the whole is then subjected to final nitriding, resulting in a 2nd stage stator as shown in Figure 12.

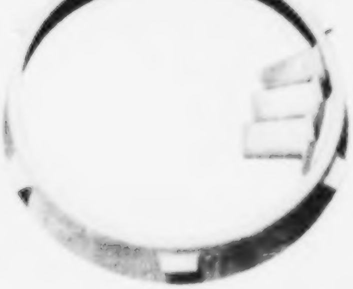

Fig. 11 "Vanes & Shroud for Inverted Channel 2nd Stage Stator"

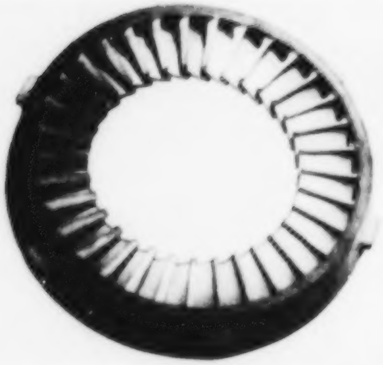

Fig. 12 "Inverted Channel 2nd Stage Stator"

Although the outer shroud had no notches and was made of high strength, slip cast material, cracking still occurred during engine testing; time to failure, however, had increased from one hour to 30 hours.

Because cracking appeared to be a time-dependent problem, an "inverted channel" stator was soaked in an air furnace at 1035°C. Results of this test showed that an axial crack occurred in the outer shroud after 75 hours, very similar to that experienced during engine testing. This cracking was thought due to a mismatch between the injection molded vanes and somewhat higher density slip cast outer shroud. Therefore, a stator was fabricated with vanes and outer shroud of matched density; this stator has successfully withstood a furnace soak test for over [illegible] hours with no indications of cracking; a similar stator has been fabricated for tests in an engine.

CERAMIC TURBINE ROTORS

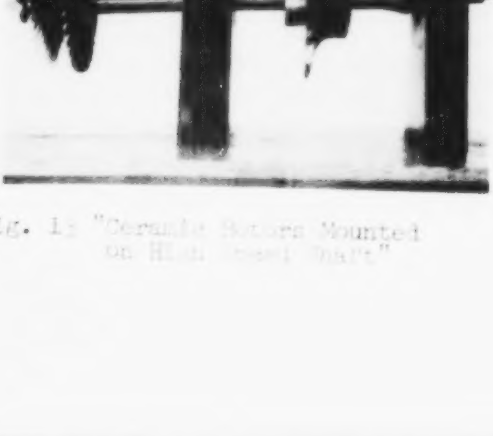

Fig. 13 "Ceramic Rotors Mounted on High Speed Shaft"

Both 1st and 2nd stage, all-ceramic turbine rotors are mounted to the high speed shaft at the opposite end from the aluminum radial compressor, as shown in Figure 13. The ceramic rotors are concentrically located by curvic couplings and attached to the shaft by a special folded bolt. Major emphasis has been placed on the "duo-density" rotor concept where high-strength, hot pressed Si_3N_4 is utilized in the highly-stressed disc, and reaction sintered Si_3N_4, which can be formed into complex shapes, is utilized for the lower-stressed blades.

Discs or hubs for duo-density rotors are now being hot pressed to shape; accuracies with a .25mm band are being achieved at the throat of the disc contour. Blade rings for duo-density rotors are being made by injection molding and reaction sintering. Molding flaws, such as entrapped gas voids and shrinkage cracks, have led to the development of careful temperature control of the tooling during molding and to a process for pre-extruding the molding compound to achieve improved homogeneity.

The most difficult fabrication problem encountered to date is the hot press bonding of the hub to the blade ring. A graphite wedge system, as shown in Figure 14, was developed for this bonding process.(8) In this system, independent pressures can be applied to the hot pressed Si_3N_4 hub and, through tapered graphite wedges, to the reaction sintered Si_3N_4 blade ring. Although at conditions of 1650°C for two hours with pressures of 15-20 MN/m^2, good bonding quality could be achieved, tearing and/or deformation of the blade ring could not be avoided. It was apparent that the entire rim of the blade ring needed support during hot press bonding; to do this, slip cast Si_3N_4 blade inserts were developed, as shown in Figure 15, as a reinforcing media which could be removed after hot press bonding. Several duo-density rotors have been made using this technique, and some have shown excellent bonds between the hub and blade ring. However, results to date indicate that alignment during hot press bonding is critical as is the need to match hub and wedge pressures.

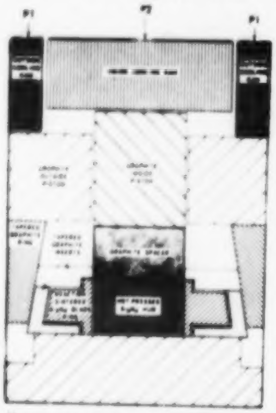

Fig. 14 "Graphite Wedge System for Hot Press Bonding"

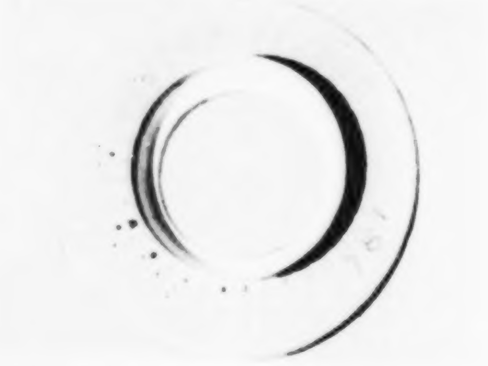

Fig. 15 "Reinforcing Inserts for Hot Press Bonding"

Spin testing of ceramic rotors(9) has been carried out in a spin pit at room temperature, in a partial vacuum, and at gradually increasing speed until failure occurs. A number of duo-density rotors with flat-sided hubs were cold spin tested with failure speeds as high as 55000 RPM (96%). Because failures always only occurred in the reaction sintered material and could usually be traced to fabrication defects, developments to improve the material and quality of rotor blade rings were implemented. To evaluate such improvements, provision has been made to cold spin test a blade ring on its own before bonding to a hub. For this test, blade rings are attached to a metal hub as shown in Figure 16 and bonded to the hub by an epoxy adhesive. Alternatively, segments of a blade ring can be "epoxied" to the metal hub. The result of a cold spin test of a 1st stage blade segment is shown in Figure 17, which is a photograph taken at the instant of failure at 61900 RPM (96%).

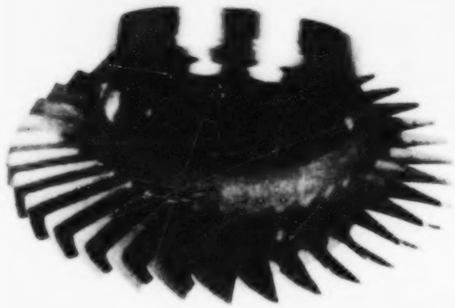

Fig. 16 "Assembly for Blade Ring Spin Test"

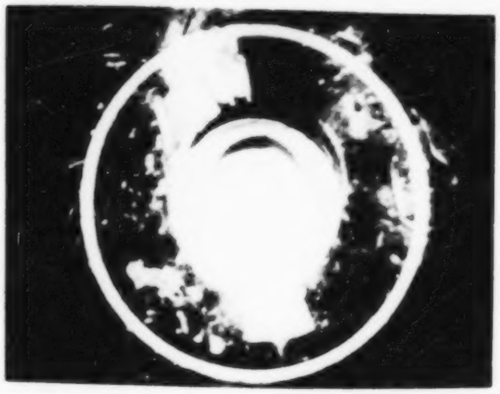

Fig. 17 "Spin Test Failure of 1st Stage Blade Segment"

Thermal shock testing of blade rings is being carried out on a thermal shock test rig. Blade rings are clamped to an indexing table, as shown in Figure 18, and are cycled into an oxy-acetylene flame for 45 secs. and then into a cold air jet. Thermal shock testing of eight blade rings has been carried out with a flame temperature of 1535°C needed to simulate the equivalent blade temperature that would occur during 1035°C starts in the engine. There was no apparent damage to any of the eight blade rings after almost 2500 thermal shock cycles.

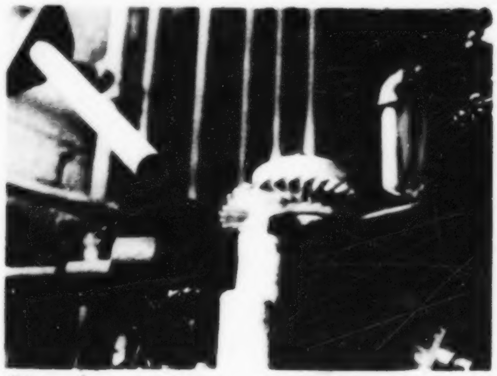

Fig. 18 Thermal Shock Testing of Blade Rings"

Hot spin testing of ceramic rotors will be carried out in a specially designed hot spin test rig. This rig uses engine hardware comprising both rotor stages mounted on the high-speed shaft, and the stationary ceramic hot flow path components. The rig has been checked out using metal rotors and is currently being built up with ceramic rotor hubs (less blade rings) to hot spin test the curvic couplings and folded bolt attachment.

In addition to the development of duo-density silicon nitride turbine rotors reported above, other approaches are being investigated and include both silicon nitride and silicon carbide materials.

ENGINE TEST OF CERAMICS

Recently, a major milestone in the program was accomplished. This milestone called for a 50-hour cyclic durability test of the high temperature gas turbine engine using metal turbine rotors and a complete set of ceramic stationary flow path components. The test comprised 10 cold starts, 3 hot starts, and 50 one-hour cycles during which engine speed was automatically varied from idle to 90% (58000 RPM) and turbine inlet temperature was automatically controlled to a flat steady-state schedule of 1050°C. Inspection of the ceramic components after the 50-hour test revealed that all of the parts except the 2nd stage stator were crack-free with no apparent signs of deterioration. In the 2nd stage stator, eight of the 33 injection molded, silicon nitride stator vanes exhibited a fine trailing edge crack, though no pieces came off; the remaining 25 vanes were crack-free. An investigation into the trailing edge cracking problem is under way.

CONCLUSIONS

The program to develop materials, fabrication processes, and designs to apply ceramics to a vehicular, high temperature gas turbine engine is well under way. The stationary ceramic components have been through all of the development phases, including a 50-hour engine test. Ceramic turbine rotors have been through the design phase and are currently in the phase of fabrication development and initial component testing. Some of the real problems of fabricating a duo-density silicon nitride turbine rotor have been defined and are being worked on.

The reality of a high temperature, gas turbine engine using ceramics is more promising today as a result of this program and the progress made to date.

ACKNOWLEDGMENTS

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Rankine Cycle Power Systems with Organic Based Working Fluid for Automotive Systems

P. S. Patel
M. J. Armstrong

Thermo Electron Corporation
101 First Avenue
Waltham, Massachusetts 02154. U. S. A.

An automotive powerplant using an organic Rankine-cycle system has been designed, built, and tested in a preprototype configuration. A description of the system and results of system testing are presented. Emission results show that the system could meet the 1977 emission standards specified by the U. S. Congress in the 1970 Clean Air Act. Another application of the organic Rankine engine as a bottoming cycle operating on waste exhaust energy from a heavy duty truck diesel engine is described. The combined cycle results in a 15% improvement in fuel economy and emissions over a wide load range.

This paper describes two applications of organic Rankine-cycle power systems. The organic Rankine-cycle engine for passenger automobile propulsion is described first. Next, application of an organic Rankine-cycle power system as a bottoming cycle for a heavy duty diesel truck engine is presented.

I. ORGANIC RANKINE-CYCLE POWER SYSTEM FOR AUTOMOBILE PROPULSION

A. SYSTEM DESCRIPTION

The Thermo Electron Rankine-cycle engine is a completely sealed system using an organic working fluid. A schematic diagram of the engine is illustrated in Figure 1. The major system components consist of the burner-boiler, expander, feedpump, condenser, and regenerator. Organic vapor from the boiler is expanded in a reciprocating expander to produce the power to drive the vehicle, all auxiliaries and accessories. Superheated vapor exhausts from the expander into the regenerator, where part of the energy in the exhaust vapor is transferred

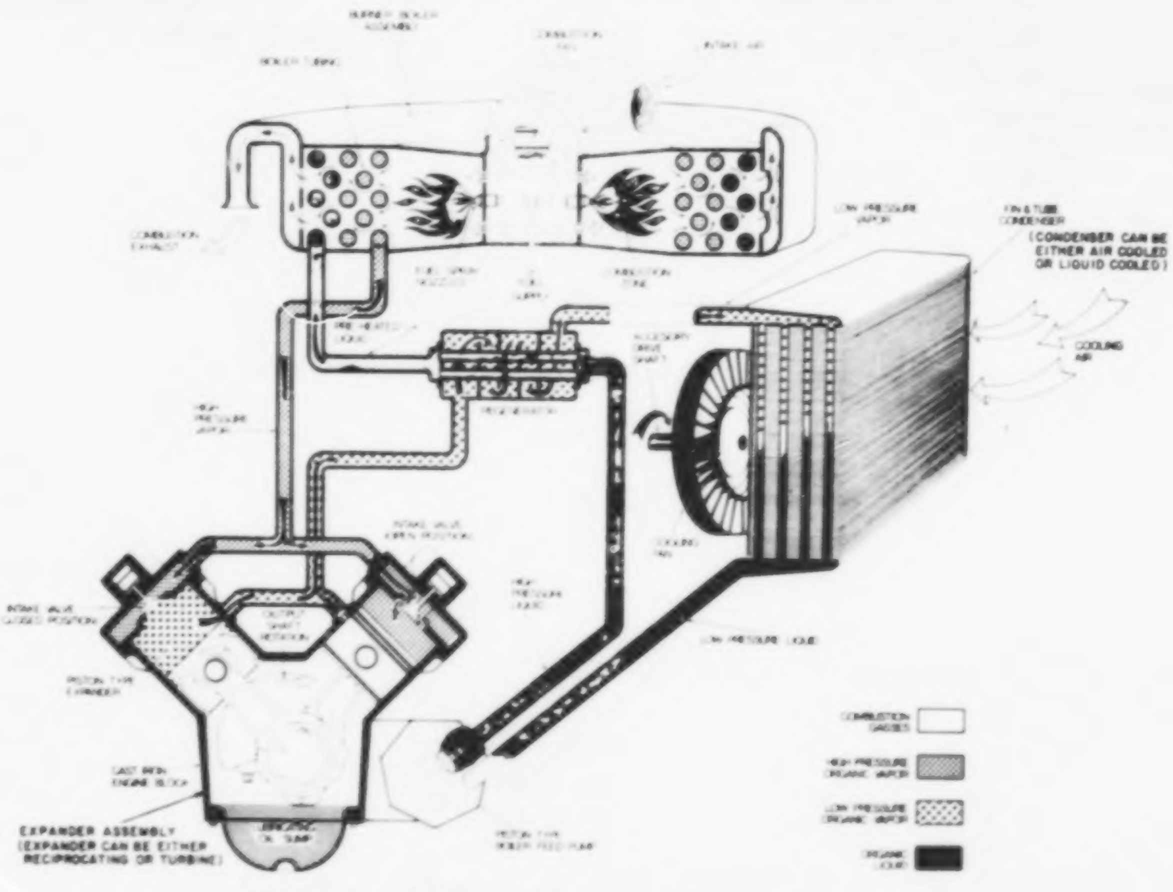

LOW PRESSURE VAPOR
FIN & TUBE CONDENSER
(CONDENSER CAN BE EITHER AIR COOLED OR LIQUID COOLED)
COOLING AIR
LOW PRESSURE LIQUID
EXPANDER ASSEMBLY (EXPANDER CAN BE EITHER RECIPROCATING OR TURBINE)
COMBUSTION GASES
HIGH PRESSURE ORGANIC VAPOR
LOW PRESSURE ORGANIC VAPOR
ORGANIC LIQUID

Figure 1. Thermo Electron Rankine-cycle Engine Schematic Diagram

to the feet liquid going to the vapor side of the regenerator with slight superheat and passes into the air-cooled condenser where the remaining superheat is removed and the vapor is condensed to liquid with some subcooling. The condensed liquid pressure is then raised from the condenser pressure to the boiler inlet pressure by the system feedpump. The liquid then passes through the liquid side of the regenerator and into the vapor generator; energy transferred to the working fluid by fuel combustion gives the vapor generator outlet conditions, completing the cycle. The system is completely sealed with 100% of the vapor condensed under all operating conditions.

The working fluid used is Fluorinol-85, a mixture of 85 mole % trifluoroethanol and 15 mole % water. This fluid has excellent characteristics as the working fluid for low-cost Rankine-cycle engines oriented to commercial applications. Its thermodynamic characteristics provide an acceptable cycle efficiency at moderate boiler outlet temperature levels of 500-625°F. At these temperatures, low-cost lubricants are available which are thermally stable and compatible with the working fluid at the peak cycle temperature. A lubricant is thus sealed in the system with the working fluid without the necessity for complete separation of the lubricating oil from the working fluid before entering the boiler. All internal moving parts of the system are well lubricated, providing potential for long life. The moderate boiler outlet temperature, coupled with the noncorrosiveness of the working fluid, also permits use of low cost materials of construction, such as carbon steel boiler tubing and cast iron expander block, minimizing the system cost. Another key characteristic for the automotive application is the low freezing point of -82°F.

Performance calculations indicate that a system designed to provide 146 gross shaft power from the expander at a vehicle speed of 107 mph and expander speed of 1800 rpm provides acceptable performance when installed in the reference vehicle, the 1972 Ford Galaxie. All component sizes are based on this peak power design point condition. The peak cycle pressure and temperature at the expander inlet are 700 psia/625°F.

B. TEST RESULTS

The preprototype engine is being tested at Thermo Electron's automotive Rankine-cycle engine development facility. The facility has been designed to conduct steady-state tests over the entire operating range of the preprototype engine. Instrumentation has been installed to determine accurately the prototype engine performance, the fuel consumption, and the exhaust emissions as well as the performance of individual components. In the preprototype tests, the expander is coupled directly to the dynamometer, and the dynamometer measures the torque and speed that would occur at the expander-to-transmission step-up gear interface in an automotive installation. A condenser ram air facility has been constructed as part of the preprototype test facility. It can simulate ram air velocities up to 90 mph. Warm air from the condenser outlet can be recirculated to the ram air blower inlet in order to control the condenser cooling air temperature.

The test range has included cruise and acceleration conditions covering speeds from idle to 70 mph, inlet pressures from 400-700 psia, and maximum inlet temperatures to 625°F. Expander driven auxiliaries include: condenser fans, feedpump, lube oil pump, alternator, and hydraulic pump for valves. The test system is close-coupled and arranged as it would be in the vehicle installation.

The two key test measurements are the fuel economy and the emissions. The measured fuel economy corresponding to the road load for various vehicle speeds is shown in Figure 2. As can be seen from Figure 2, about 50% improvement in fuel economy has been attained since the start of the test program as a result of hardware modifications and system improvements.

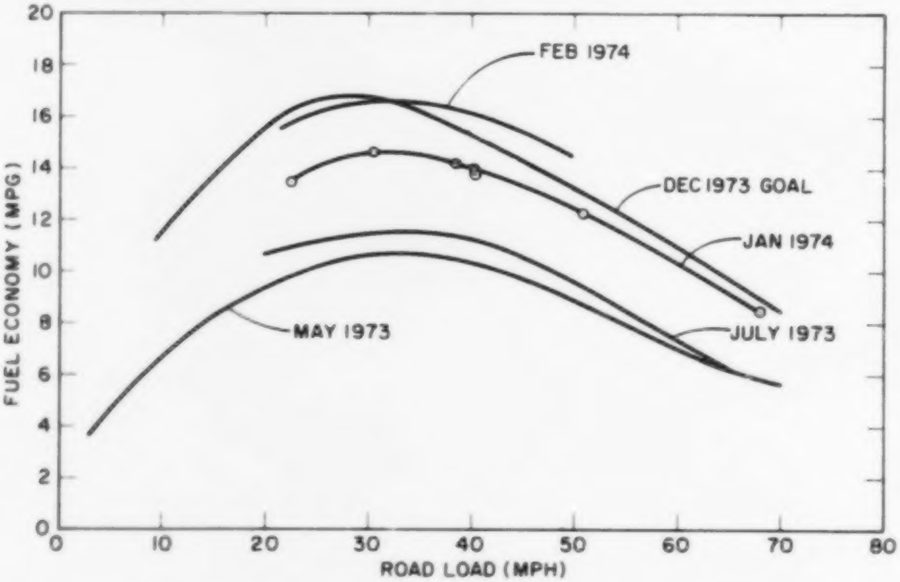


Figure 2. Preprototype System Fuel Economy

The steady-state emission measurements were used as an input to a computer program to project emission levels over the Federal Driving Cycle used by the U. S. Environmental Protection Agency. The results are shown in Table 1. The emission levels shown include 30 seconds firing at 58 lbs/hr for start-up simulation and show pollution levels well below 1977 U. S. standards.

TABLE I

EMISSIONS FOR FEDERAL DRIVING CYCLE

Pollutant	1977 Federal Standard (Grams/Mile)	(Grams/Mile) Emissions
UHC	0.41	0.17
CO	3.40	0.21
NO_x	0.40	0.275

1. Based on steady state test data.
2. Includes 30 seconds firing at 58 lbs/hr for start-up simulation.
3. Fuel consumption 10.2 MPG for Federal driving cycle.

II. DIESEL-ORGANIC RANKINE COMBINED CYCLE POWER PLANT FOR HEAVY DUTY TRUCKS

A. INTRODUCTION

Increasing emphasis on improving both fuel economy and emissions provides a strong incentive for development of systems that convert currently wasted energy in automotive vehicles to useful power.

The major portion of the waste energy in an internal combustion engine is associated with the exhaust gases. This exhaust energy is available at temperatures in the range from 700°F to 1500°F at full load, depending upon the type of internal combustion engine. However, at the off-design power levels encountered in typical duty cycles the exhaust gas temperature drops significantly. Thus the maximum temperatures available for use in the waste heat recovery process are limited. For automotive application, the sink temperature would correspond to the maximum ambient temperature at which the system is expected to operate. Therefore, any practical waste heat utilization system would have to perform efficiently in a relatively low temperature range. This indicates a Rankine-cycle temperature range of 650°F boiler/180°F condenser.

The organic Rankine-cycle system (ORCS) offers the best potential for utilizing the internal combustion engine exhaust energy due to its relatively high cycle efficiency at moderate peak cycle temperatures of 550°F to 650°F. The thermodynamic properties of the proposed organic fluid, Fluorinol-50, (50 mole percent trifluoroethanol and 50 mole percent water) which has a low latent heat requirement, make it possible to extract the maximum heat at the highest possible pressures and temperatures for a given exhaust temperature. In a thermodynamic sense, this means that the temperature difference between the exhaust gas and the organic fluid is held to a minimum during the heat addition process, thereby reducing the thermodynamic irreversibilities. This is illustrated in Figure 3 which compares the temperature profiles in an exhaust heat recovery vapor generator for both organic and water systems.

The organic Rankine bottoming cycle can be considered for various automobile and truck applications. The most attractive use, however, is in large, heavy-duty diesel trucks for long distance hauling. Here, the engine load and speed requirements are nearly constant over a large portion of the operating hours, and high mileages are accumulated. Thus, the potential fuel savings are sufficient to justify the added cost of a bottoming cycle system.

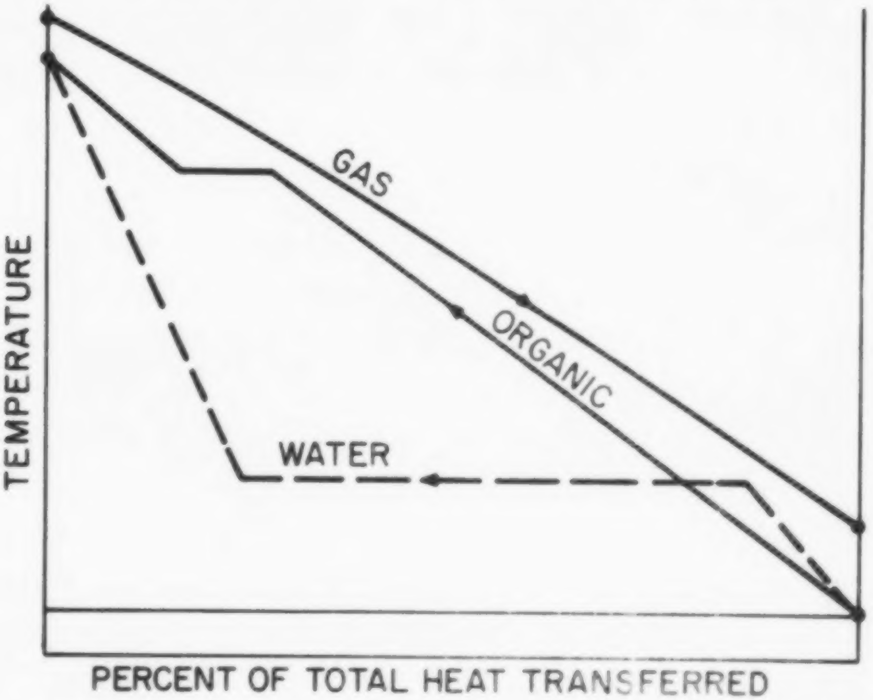


Figure 3. Schematic of Vapor Generator Temperature Profiles for Organic and for Water Working Fluid

B. SYSTEM DESCRIPTION AND PACKAGING

For the preliminary design of an ORCS, a 675 CID, 230 hp Mack Truck diesel engine was selected. Characteristics of this diesel engine are shown in Figure 4. This engine was chosen primarily because its horsepower rating is representative of the typical engine used for this application. Also, this engine has excellent BSFC characteristics.

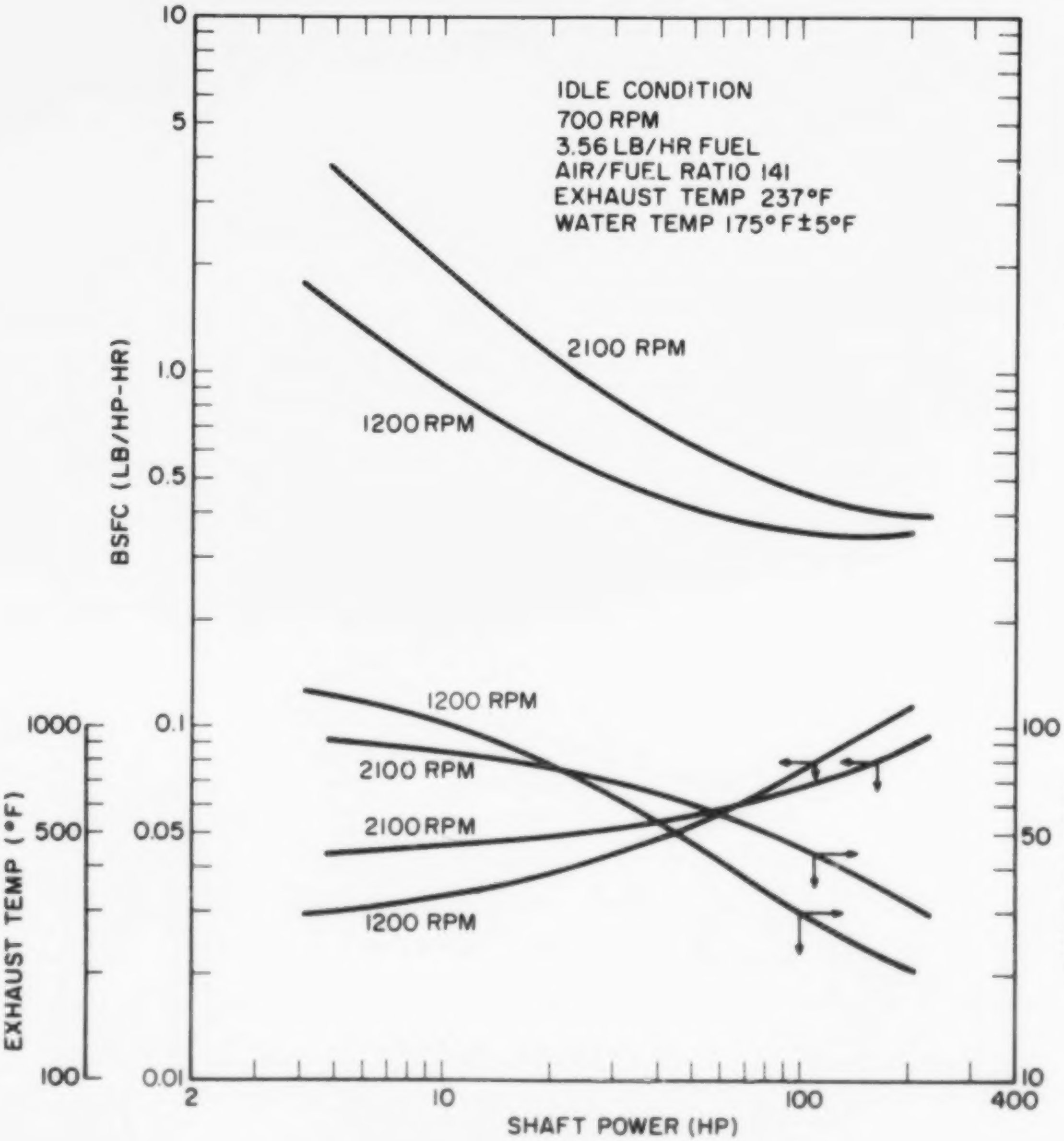


Figure 4. Characteristics of Mack 675 CID Truck Diesel Engine

A schematic of the ORCS-Diesel compound engine is shown in Figure 5. The working fluid used, Fluorinol-50, has thermodynamic characteristics that provide good cycle efficiency at low peak temperatures, high thermal stability, compatibility with low-cost commercial lubricants, low regenerator requirements, low freezing point, and attractive boiler pinch-point considerations.

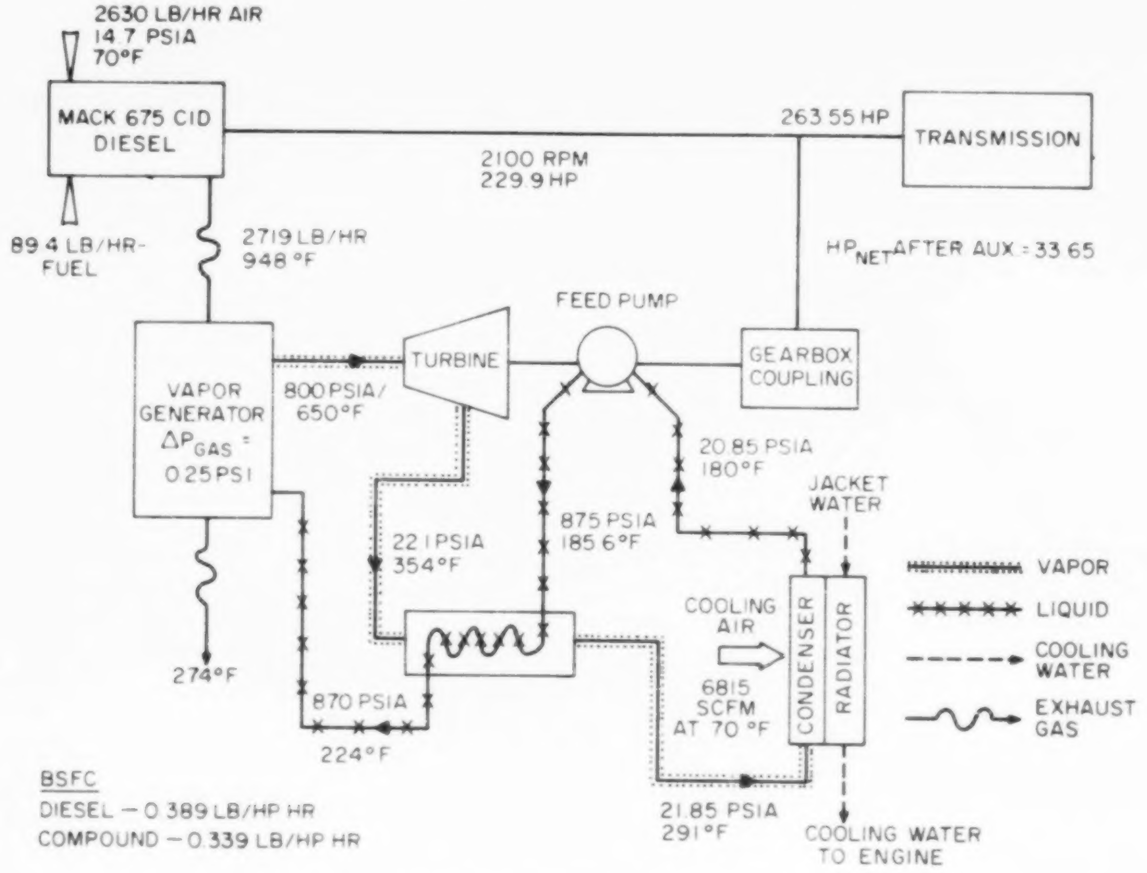


Figure 5. Diesel-Organic Rankine Compound Engine Flow Schematic

A summary of the design point characteristics of an ORCS/Diesel compound engine is shown in Table 2. At a peak cycle temperature of 650°F and a pressure of 800 psia, the ORCS improves the diesel BSFC by 14.64%. At part-load, approximately 25% of the design power, the exhaust gas temperature from this Mack diesel has decreased to 572°F. For this part-load operation, it is necessary to reduce the peak cycle temperature and pressure to approximately 450°F and 300 psia, resulting in the part-load characteristics shown in Table 3. Even at this low power point, however, the addition of ORCS results in a 14.84% improvement in fuel economy.

TABLE 2

DESIGN POINT CHARACTERISTICS OF ORCS-DIESEL COMPOUND ENGINE

DIESEL ENGINE	675 CID MACK
Design Horsepower	229.9 hp
BSFC	0.389
Efficiency (Based on LHV)	35.55%
RPM	2100
Air Flow Rate	2630 lb/hr
Fuel Flow Rate	89.4 lb/hr
Exhaust Gas Temperature	948°F
ORCS NET POWER	33.65 hp
ORCS-DIESEL COMPOUND ENGINE	
Horsepower	263.55 hp
BSFC	0.339
Efficiency (Based on LHV)	40.75%
FUEL ECONOMY IMPROVEMENT DUE TO ORCS	14.65%

TABLE 3

PARTLOAD CHARACTERISTICS OF ORCS-DIESEL COMPOUND ENGINE

DIESEL ENGINE	675 CID MACK
Horsepower	57.6 hp
BSFC	0.572 lb/hp-hr
Efficiency (Based on LHV)	24.16%
RPM	2100
Air Flow Rate	1882 lb/hr
Fuel Flow Rate	32.97 lb/hr
Exhaust Gas Temperature	572°F
ORCS NET POWER	8.55 hp
ORCS-DIESEL COMPOUND ENGINE	
Horsepower	66.15 hp
BSFC	0.498 lb/hp-hr
Efficiency (Based on LHV)	27.75%
FUEL ECONOMY IMPROVEMENT DUE TO ORCS	14.84%

Since the duty cycles for most heavy duty trucks require engine operation in the range of 25% to 100% of maximum power, an improvement of more than 14% in fuel economy over the duty cycle could be expected. Emission levels will also be reduced by an amount at least equal to the gains in efficiency. A further advantage of the combined cycle system is that no modifications are required to the basic diesel engine.

Figure 6 shows the packaging layout of ORCS-Diesel Compound Engine. The vapor generator is integrated with the muffler for the diesel engine, and is expected to contribute significantly to muffling the diesel exhaust noise, permitting use of a smaller conventional muffler. This approach minimizes additional packaging space requirements, and makes use of the pressure drop assigned for the muffler. Thus, the vapor-generator serves a dual function. The feedpump, expander. and regenerator are mouneted on the driver's side of the diesel engine and the condenser/radiator combination is mounted in the same location as the current radiator. The ORCS-diesel compound engine is shown in a Mack truck with the cab lifted in Figure 7.

The preliminary system design has established the basic feasibility of the approach with respect to component sizes, fuel economy and emissions improvement.

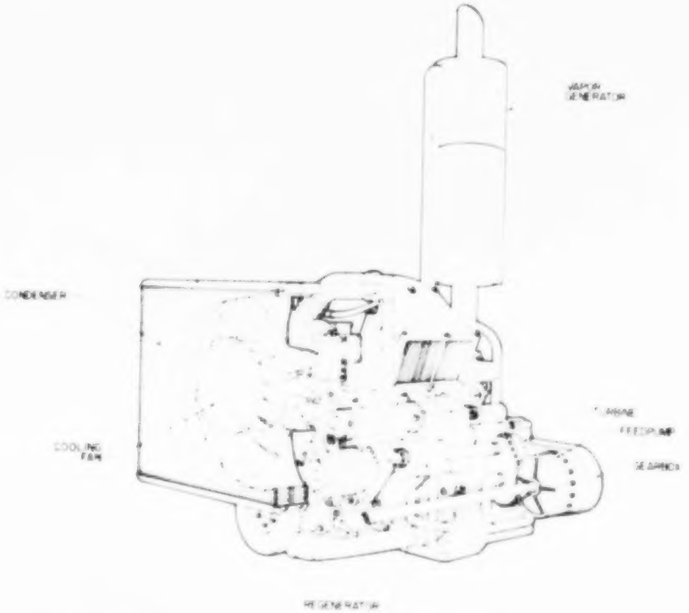


Figure 6. Packaging Layout of ORCS Diesel Compound Engine Power Plant

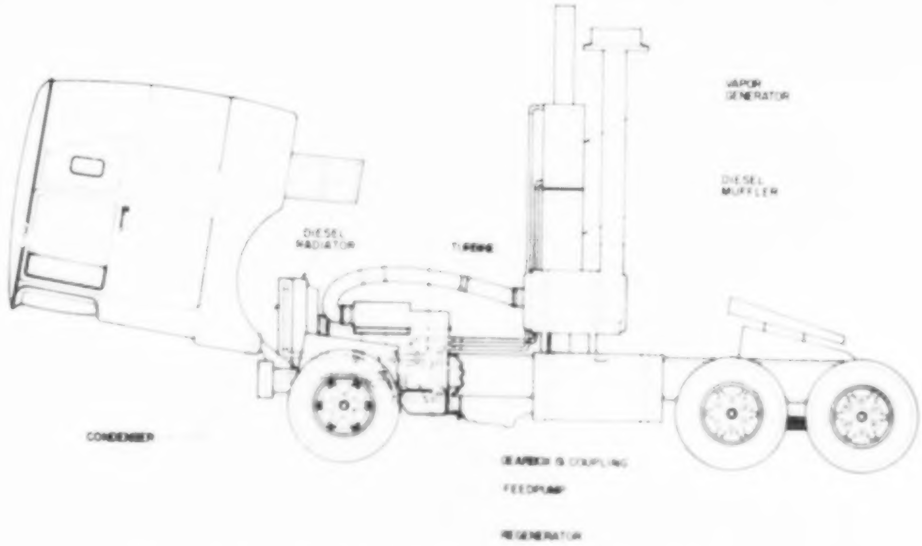


Figure 7. ORCS-Diesel Compound Engine in a Mack Truck with Cab Lifted Over

APPENDIX

BSFC	Brake Specific Fuel Consumption lb/hp-hr
CID	Cubic Inch Displacement
CO	Carbon Monoxide
LHV	Lower Heating Value
MPG	Miles per Gallon
MPH	Miles per Hour
NO_x	Nitrogen Oxides
ORCS	Organ Rankine Cycle System
RPM	Revolutions per Minute
SCFM	Standard Cubic Feet per Minute
UHC	Unburned Hydrocarbons

RECENT PROGRESS IN DEVELOPMENT OF THE EPA PROGRAM ON LOW EMISSION AUTOMOTIVE STEAM ENGINES

LAWRENCE C. HOAGLAND
Scientific Energy Systems Corporation
570 Pleasant Street
Watertown, Massachusetts 02172

SUMMARY

Progress to date is summarized on a U.S. Environmental Protection Agency program to develop an automotive steam engine employing a 4-cylinder uniflow reciprocating expander and a unique low-emission homogeneous combustor. Extensive system testing on an engine dynamometer has shown that this system yields exhaust emissions less than 1/2 of the U.S. Federal standards for 1978 while producing fuel economy and acceleration performance substantially equal to current emission controlled gasoline engine vehicles. The system will soon be installed in a 2100 kg car for chassis dynamometer tests and control system development.

RESUME

Progrès à ce jour sont récapitulés au sujuet d'un programme de développement de la Environ de Protection Agency pour developper une machine a vapeur automobile utilisant un extensomètre de récuperage à quatre cylindres avec chambre de combustion homogène à faible émission de gaz. Des tests approfondis sur le dynamomètre d'un moteur ont démontré que ce systeme produit moins de la moitié des taux de gaz d'échappement éstablis par les standards féderaux des Etats-Unis pour 1978, tout en produisant une économie de carburant et une puissance d'acceleration égale à celle des véhicules munis de moteur à gazoline avec contrôle des gaz d'échappement. L'appareil sera bientôt installé dans une automobile de 2100 kg afin d'effectuer des tests dynamométriques du chassis et de développer le système de contrôle.

ZUSAMMENFASSUNG

Der bisher erzielte Fortschritt wird durch ein Programm der amerikanischen Umweltschutzbehörde (EPA) ausgedruckt, das sich die Entwicklung einer Auto-Dampfmaschine zur Aufgabe stellt, die auf einem vierzylindrigen Gleichstrom-Kolbenexpander und einer einzigartigen homogenen Verbrennungskammer mit niedriger Abgasentwicklung beruht. Umfangreiche Systemüberprüfungen auf einem Dynamometer bewiesen, dass dieses Antriebssystem weniger als die Hälfte der in der U.S. Norm für 1978 begrenzten Abgase erzeugt, wahrend Wirtschaftlichkeit und Beschleunigungsverhalten in etwa den Werten für heutige abgasgeregelte Verbrennungsmotern entsprichen. Dieses System wird in Kürze in einen 2 t schweren Wagen eingebaut.

SYSTEM DESCRIPTION

The EPA steam powerplant currently undergoing test and development at Scientific Energy Systems (SES) incorporates the following general features:

1. Pure water as the working fluid. Although water freezes within the normal operating temperature range, its superior thermodynamic, thermal stability and heat transfer properties make it an attractive choice over other presently known fluids. The superior thermodynamic and heat transfer properties of water are responsible for the achievement of higher thermal efficiency and more compact system hardware than has been attained using other working fluids. The freezing problem is adequately handled by proper design for drainage into an insulated sump and the use of a small, automatic heater which prevents freezing and the attendant inconvenience.

2. High pressure, high temperature steam conditions (6900KPa, 538°C) for compactness and efficiency.

3. A 4-cyl, single-stage reciprocating uniflow expander employing a conventional automotive "trunk-type" piston with the steam cylinder, engine crank bearings, and cam surfaces all lubricated by a common crankcase oil. Output power is controlled by regulating the period of inlet steam flow through poppet valves during the expansion stroke (variable cutoff).

4. Expander-driven auxiliaries and accessories such as the feed pump, alternator, air-conditioning compressor, power steering, and power brakes. The expander idles to drive the accessories at zero road speed; a three-speed automatic transmission provides for suitable acceleration and part-load economy characteristics.

5. A highly compact burner/vapor generator package incorporating features which reduce the total length of heat transfer tubing, provide efficient utilization of space, and provide excellent control over emissions, especially NO_x, by means of a unique, premixed homogeneous combustor.

6. An air-cooled condenser and cooling fan system capable of condensing all steam passed through the expander. A variable-speed drive on the fans and a floating condenser pressure permit a fully condensing system with reasonable condenser size and peak fan power, while allowing for reduced fan power and improved fuel economy during cruise conditions.

7. Automatic controls for all functions except operator control over expander steam flow by varying intake valve cutoff.

A schematic diagram of the powerplant is shown in Fig. 1. Major system components are the expander, burner/vapor generator, condenser and feed pump, which are arranged in a closed loop as illustrated. The expander drives the the vehicle through a conventional three-speed automatic transmission and dif-

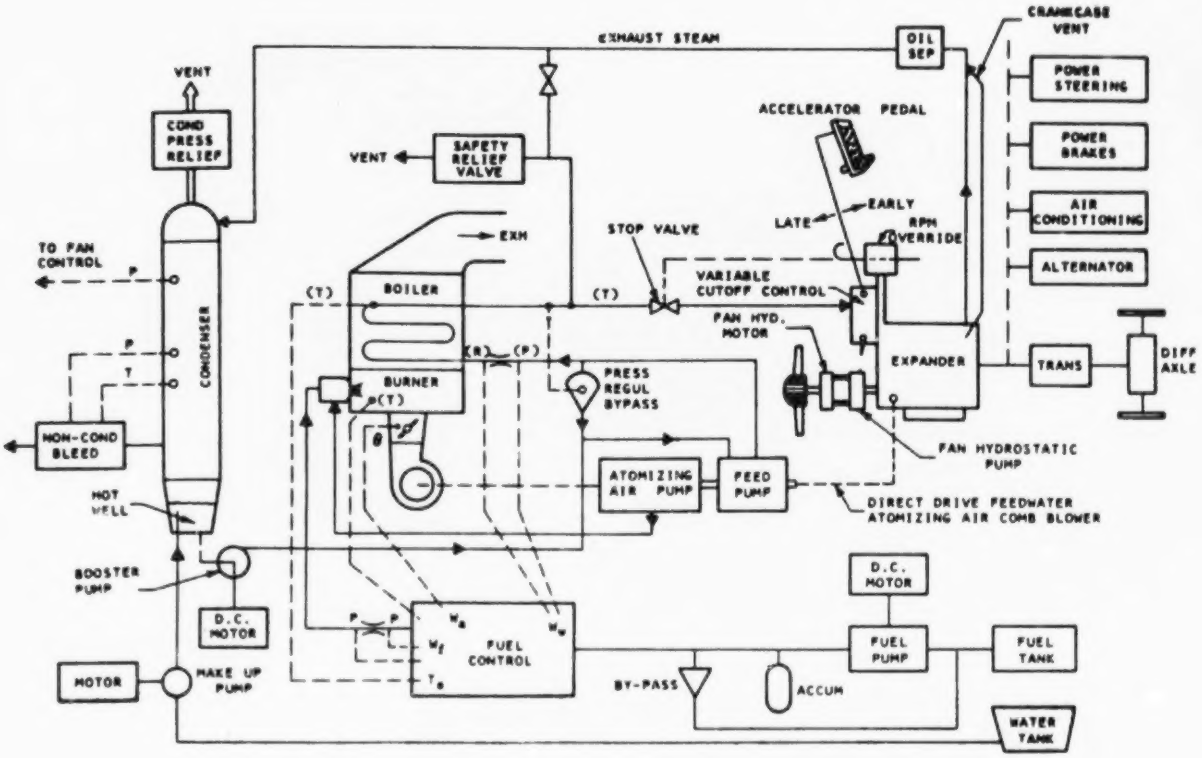


FIG. 1 - STEAM POWERPLANT SCHEMATIC DIAGRAM

ferential axle. Accessories such as the alternator, A/C compressor, and hydraulic pump for steering and braking assist are all belt driven from the expander, which idles when the vehicle is at rest.

Results of the latest design studies performed by Chrysler Corp. on installation of the powerplant in a 1974 Plymouth Fury are shown in Figs. 2-4. The expander is located adjacent to the firewall in the conventional position, but is inclined about 45 deg toward the left side of the vehicle (Fig. 4). The cylindrical burner/vapor generator package is installed adjacent to the expander and is mounted directly to the expander so the two units move together as an assembly. This reduces the requirements for flexible high pressure steam piping between steam generator and expander. The condenser is located in the position conventionally occupied by the radiator of a water-cooled gasoline engine installation. Two condenser fans are mounted behind the condenser and driven from a hydraulic motor supplied by an expander-driven hydraulic pump. The feed pump, and combustion air blower, are expander-driven through gears and V-belt drives, as illustrated in Figs. 2 and 4. Overrunning clutches are included in the appropriate drive sheaves to enable an electric-starting motor to drive these components independent of the expander for system start-up.

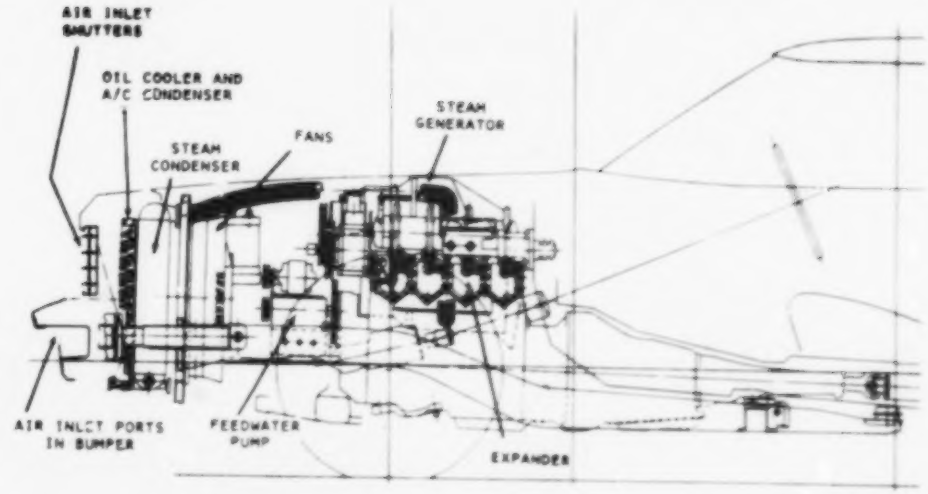


FIG. 2
LEFT SIDE
INTERIOR VIEW

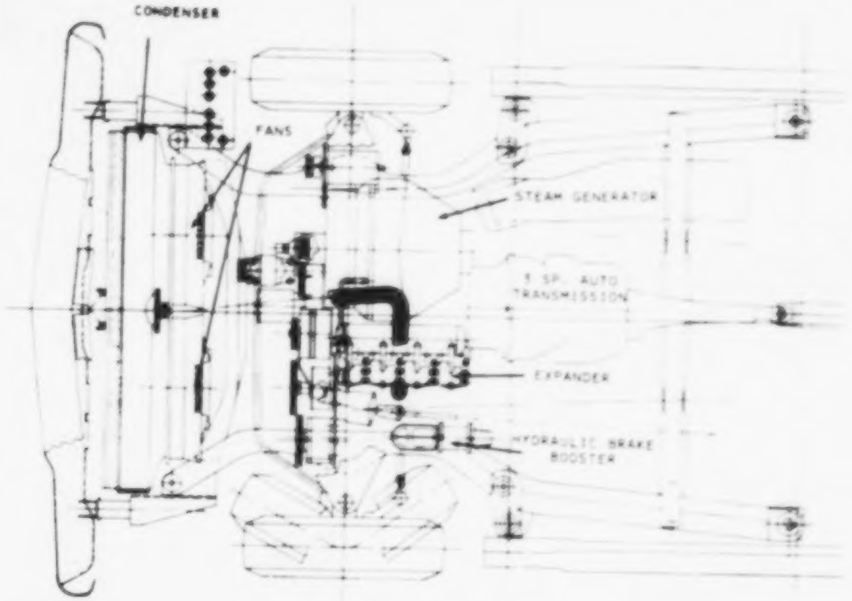


FIG. 3
TOP VIEW

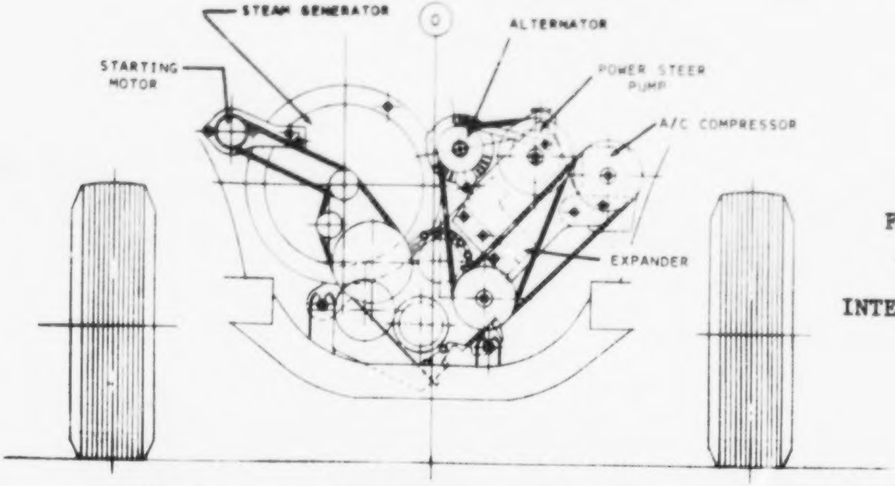


FIG. 4
FRONT
INTERIOR VIEW

FIGS. 2, 3, 4 - PROTOTYPE INSTALLATION - 1974 PLYMOUTH "C" BODY

Two condenser fans are required to cover the entire condenser air face (Fig. 3). The 1974 shock-mounted bumper is retained, and allowance is made for the 7cm rearward movement upon impact. Two air-inlet ports in the bumper provide the additional air-intake area. The grille area above the bumper incorporates air-inlet shutters which provide a means for restricting the flow of ram air under certain conditions (for example, cruise conditions at low ambient temperature), thereby maintaining higher condensing temperatures to prevent condenser freezing. The A/C condenser and transmission and engine-oil coolers are located upstream of the steam condenser and air cooled with condenser air as shown in Figs. 2 and 3.

Fig. 5 shows a photograph of the vehicle mockup with actual component hardware installed. The prototype total powerplant weight is currently estimated to be 140kg heavier than the engine it replaces. The detailed weight breakdown is shown in Table 1.

More detailed descriptions of the design features of this steam powerplant are presented in references 1, 2 and 3. The principal object of this paper is to summarize the current status of progress on this engine development program.

TABLE 1 - SYSTEM WEIGHT SUMMARY, Kg

	Preprototype	Prototype
Powerplant		
Expander	259	140
Condenser	53	38
Condenser fans	30	9
Vapor generator	75	50
Feedpump	20	7
Auxiliary drives	45	85
Working fluid, 5 gal	19	19
Lubricant	8	4
Freeze protection system	11*	11
Miscellaneous	54*	54
Total Powerplant weight	570	410
Equivalent 318 CID V-8 Engine and radiator	270	270
Additional steam system weight	300	140
Other		
Heavy-duty transmission increase	15	15
Fuel, 20 gal	57	57
Total other	72	72
Vehicle curb weight**	2152	1992

* Prototype components assumed.

** 1972 Plymouth Fury dry weight, V-8, air conditioning, and automatic transmission: 1780Kg

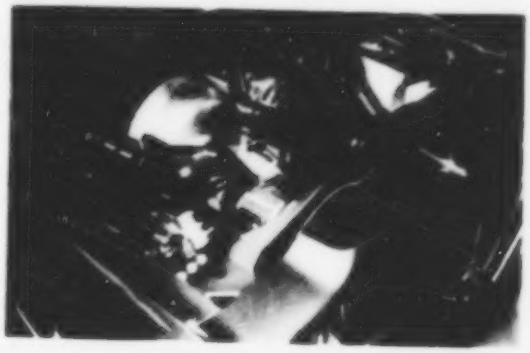


FIG. 5 - VEHICLE MOCKUP

FIG. 6 - PREPROTOTYPE SYSTEM ON ENGINE DYNAMOMETER TEST STAND

DEVELOPMENT STATUS

The initial testing and development of the system hardware is being accomplished on an engine dynamometer with an assembly designated the "preprototype system". (Fig. 6). The major components in this system are intended to represent a prototype design which would later be installed in a vehicle. Many of the ancillary components initially consisted of commercially available items but are gradually being replaced with smaller, lighter and more efficient components designed specifically for this application. The test and development program has precipitated some desired design changes to the major components which should be incorporated in a prototype engine. Weight and size reduction is the principal objective of most proposed design changes. Table 1 summarizes the expected weight reduction between the preprototype and prototype designs.

The preprototype system has been undergoing test and development over the past 18 months. The major objective of the testing has been to identify and solve problems and to improve performance and efficiency. Durability development has been a secondary objective. Several problems have been identified and resolved during that period. Some of the various improvements incorporated are: expander piston and ring design/development, expander admission valving improvement, lubrication improvements, steam leakage reduction, reduced system heat losses, steam generator efficiency increase, auxiliary component parasitic power reduction (e.g., air blower, feed pump, condenser fan drives). Over 560 hours of testing have been accumulated on the complete system (240 hours on a single build) Test and development hours accumulated on separate components are: vapor generators 2750 hours, prototype feedpumps 4300 hours, single cylinder expander 1306 hours.

EXHAUST EMISSIONS

The burner in the SES system utilizes homogeneous combustion with a premixed fuel-air mixture and a perforated plate flameholder. The firing rate is modulated continuously between idle and full load to achieve the desired control over the vapor generator output. The combustion system and vapor generator are described in references 1, 4 and 5. A low grade lead-free gasoline is the fuel used in this program, although the same combustor has also been operated successfully on kerosene and no. 2 diesel fuel.

Extensive exhaust emission measurements have been made on the burner/vapor generator assembly operating at steady state conditions under a wide range of loads and fuel-air ratios. The emissions of CO, NO_x and HC are summarized in Fig. 7 by the characteristic curves of emissions index (grams pollutant per kilogram fuel) versus percent of full load firing rate. The air-fuel ratio varies with load in a manner which minimizes the CO emissions. This schedule provides about 20% excess air at full load and about 50% excess air at idle (5% load). The sensitivity of emissions to excess air level is shown in Fig. 8 which illustrates a reasonable tolerance band within which the air-fuel ratio control system may operate without encountering significant increases in emissions.

It has been found that emissions during burner transients can be kept close to the characteristic curves of Fig. 7 by limiting the rate of change of the firing rate and by proper transient control of air and fuel flow. These factors are incorporated into the system control strategy.

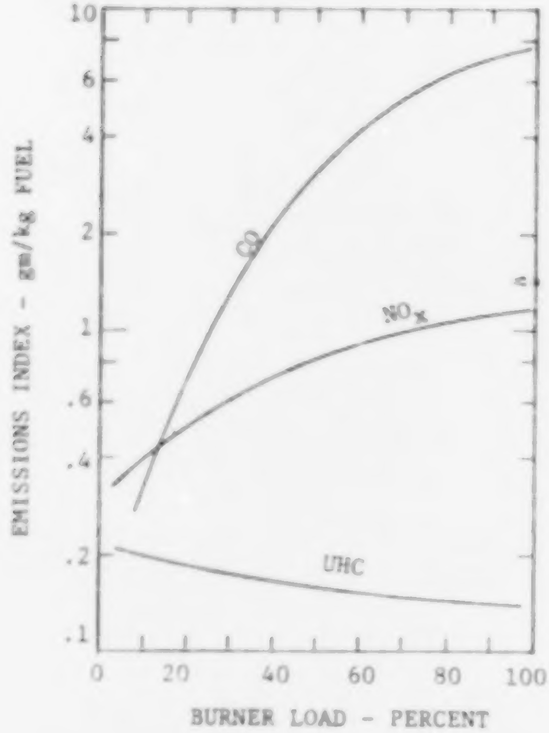


FIG. 7 - EXHAUST EMISSIONS CHARACTERISTICS OF SES BURNER AT OPTIMUM AIR/FUEL RATIO

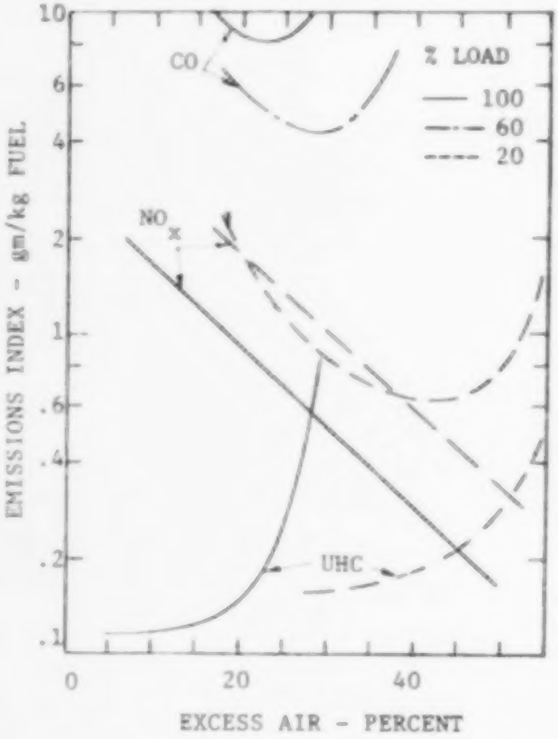


FIG. 8 - EFFECT OF EXCESS AIR ON EMISSIONS INDEX

A major portion of the total hydrocarbon emission occurs during startup and shutdown. A recent test of an automatic start and warmup cycle revealed the following total emissions during the 30 second startup period prior to the first vehicle acceleration on the Federal Urban driving cycle:

Start and Warmup emissions - UHC - 0.2 grams
(0.24 kg fuel consumed) CO - 1.9 grams
NO_x - 0.4 grams

The hydrocarbon emissions during shutdown have been measured to be about 0.25 grams.

Although the complete system has not yet been operated over the federal driving cycle (FDC) for emissions measurements, it is possible to estimate the

TABLE 2

ESTIMATED COLD START FEDERAL DRIVING CYCLE EMISSIONS-g/mile

SES STEAM ENGINE		U.S. FEDERAL STANDARDS	
		1978*	1975
NO_x	= .19	0.40	3.1
CO	= .39	3.40	15.0
UHC	= .16	0.41	1.5

* Originally 1976 but currently postponed until 1978.

FDC emissions from the above steady state data and startup, warmup and shutdown characteristics. This was done via computer simulation with the results shown in Table 2. Emissions of all three pollutant species are shown to be well below 1/2 of the 1978 "Federal emission standards", the goals set for this EPA sponsored Rankine engine program.

MEASURED SYSTEM PERFORMANCE CHARACTERISTICS

Performance testing on an engine dynamometer has resulted in the definition of a reasonably complete system power and efficiency map as well as detailed steady-speed, level-road cruise simulation at various vehicle speeds from 32 to 130 km/hr. Fig. 9 shows the latest system power map illustrating the net power into the transmission as a function of engine RPM. Lines of constant intake valve "cut-off" (crank degrees ATDC) and contours of constant brake specific fuel consumption (BSFC) are included. The vehicle road-load power characteristic is shown for an axle ratio which analysis indicates will provide the acceleration

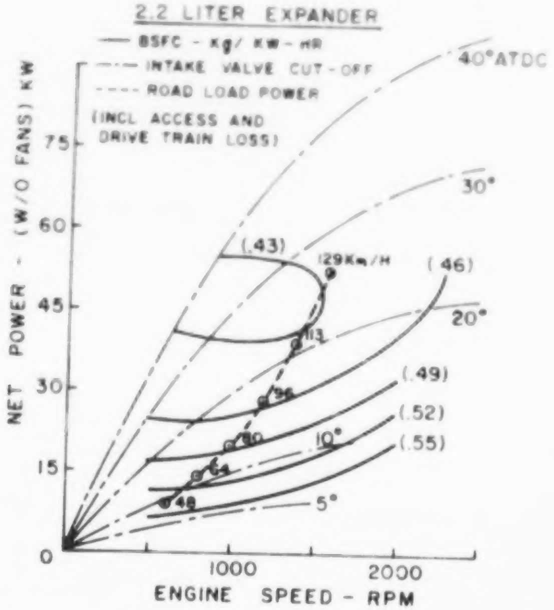


FIG. 9 - SYSTEM POWER AND EFFICIENCY MAP MEASUREMENTS ON 2.2 LITER EXPANDER

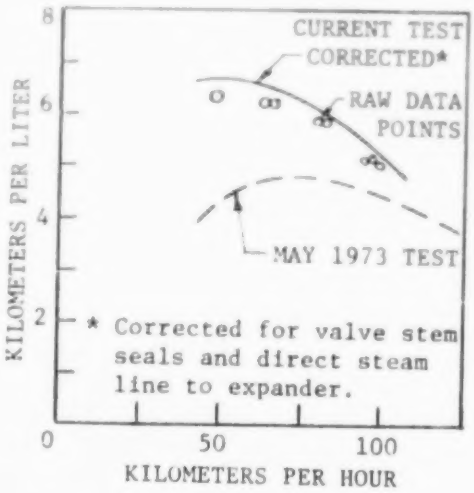


FIG. 10 - FUEL ECONOMY AT STEADY SPEED ROAD LOAD - 2100 kg CAR

characteristics specified by EPA for this program. (0-96 km/hr in 13.5 seconds).

Dynamometer testing of simulated road load cruise operation has produced the results shown in Fig. 10. To date the best demonstrated fuel economy is 6.7 km/l at 48 km/hr.

FUTURE IMPROVEMENTS

The performance map for the current preprototype engine (Fig. 9) reveals that the best efficiency point occurs at a relatively high power level (45 kW) compared with the power level of 25 kW required for level road cruise at the current USA speed limit of 88 km/hr. A smaller displacement expander would achieve its best efficiency at a lower power level, thereby yielding improved fuel economy during steady speed cruise. To maintain acceleration performance, the same maximum power output capability could be retained by employing later cut-off (with reduced efficiency) at full power. An example of what can be achieved by this means is illustrated by the estimated power map for an expander with half the displacement of the current 2.2 liter preprototype unit (Fig. 11). The best BSFC island is shifted down to 30 kW and acceleration power is maintained by increasing the maximum cut-off from about 40° ATDC to 60° ATDC. Table 3 shows a comparison of the BSFC values for road load operation at various vehicle speeds. A fuel economy improvement of about 7-9% is indicated in the speed range of 50 to 100 km/hr. More extensive studies of optimum expander size are currently being conducted as part of the prototype engine design task.

In addition to improved expander performance studies, an improved steam generator is currently being fabricated. It features 1) aluminum fins in the economizer section, 2) a revised pass arrangement, and 3) a water by-pass circuit between the economizer and superheater (Fig. 12). All of these features

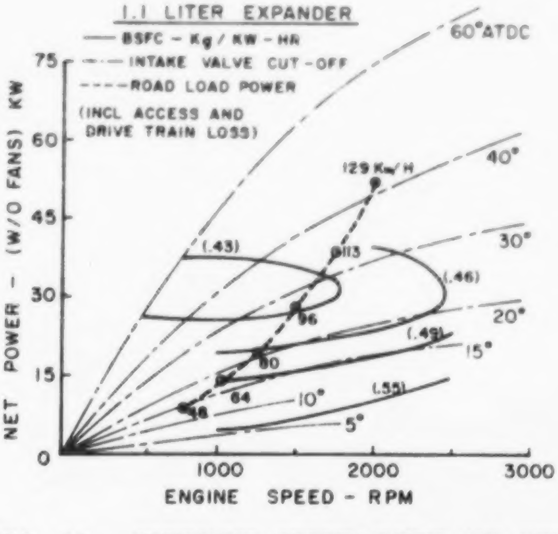


FIG. 11 - ESTIMATED SYSTEM POWER AND EFFICIENCY MAP FOR 1.1 LITER EXPANDER

TABLE 3

EFFECT OF REDUCED EXPANDER DISPLACEMENT ON ROAD LOAD FUEL CONSUMPTION

Vehicle Speed km/hr	Road Load BSFC-kg/kW-hr	
	2.2 Liter Exp.	1.1 Liter Exp.
50	.54	.50
65	.51	.470
80	.49	.44
95	.46	.43
110	.43	.440

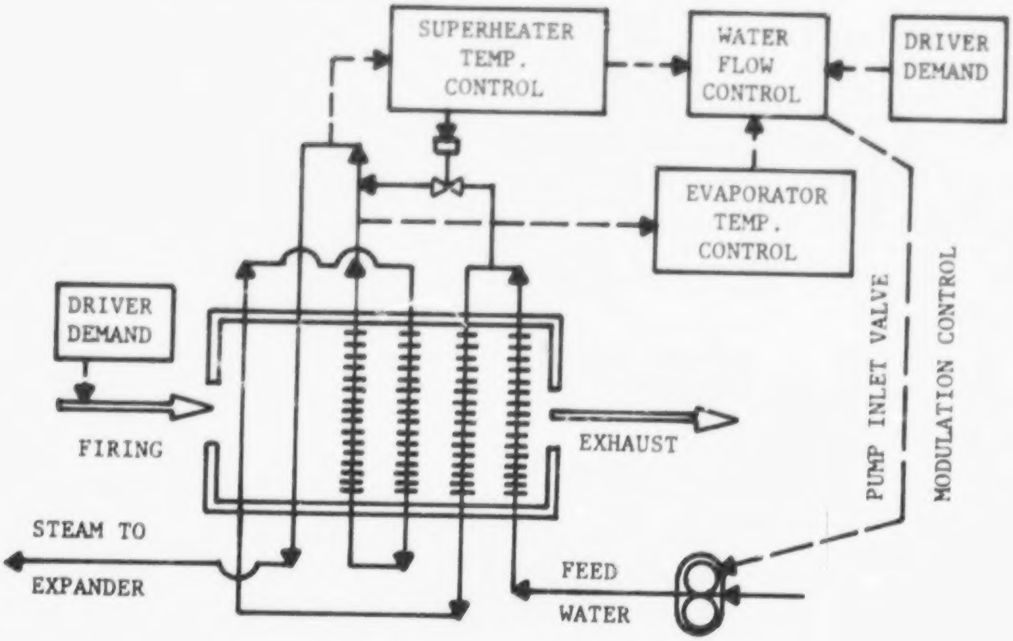
were devised to reduce the stored thermal energy change between load levels in an effort to provide a substantial improvement in transient response characteristics. Greatly improved system controlability is expected to result.

FIG. 12A - IMPROVED RESPONSE BOILER

- STRATEGY
  - Energy Leveling
    1. Reduced Tube Weight
    2. Revised Pass Order
    3. Passive Evaporator Bypass
  - Control Options
    1. Active Evaporator Bypass Control
    2. Variable Boiler Pressure to Level Energy Change
- COMPARISON OF CURRENT MODEL 5 AND NEW MODEL 7 BOILERS

	MODEL 5	MODEL 7
- Maximum Steam Flow	20 lb/min	20 lb/min
- Tubing Weight	98 lb.	61 lb.
- Metal Energy Change, Idle to Full Load	1,430 BTU	100 BTU
- Superheater Temperature Control Point	Exit	Inlet

FIG. 12B - MODEL 7 BOILER AND CONTROL STRATEGY



VEHICLE INSTALLATION

Work is currently underway to install the preprototype engine in a modified 1974 Plymouth Fury for chassis dynamometer testing and control system development under transient driving conditions. This system, designated a "Controls Simulator", is scheduled to begin chassis dyno tests in the spring of 1975.

ACKNOWLEDGEMENTS

The work reported in this paper is being sponsored by the U.S. Office of Air Programs of the Environmental Protection Agency - Alternative Automotive Power Systems Division, Ann Arbor, Michigan, under contract no. 68-04-0004; S. Luchter, project officer. The valuable assistance of Chrysler Corporation, Ricardo Consulting Engineers, Ltd., and Esso Research and Engineering Co., as major subcontractors is also gratefully acknowledged.

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The Potential of the Philips Stirling Engine for Pollution Reduction and Energy Conservation

R.J. Meijer and C.L. Spigt
Philips Research Laboratories, Eindhoven, Holland

Paper presented at the Second Symposium on Low Pollution Power Systems Development organized by the Committee on the Challenges of Modern Society of the North Atlantic Treaty Organization in Dusseldorf, Germany, November 4-8th 1974.

Summary

This paper gives a general description of the potential of the Philips Stirling engine, of the development of the engine through the years and of the present state of the art. In more detail the multifuel capabilities coupled with the low emission potential are discussed. As an example of the variety of external heating possibilities which exist with this engine, a zero pollution automobile propulsion unit is described using a new concept of a Stirling engine with a variable swash-plate and heated by a rechargeable thermal storage unit. Hardware developments and performance characteristics of such a propulsion unit are given.

Résumé

Le présent article contient une description générale des possibilités offertes par le moteur Stirling Philips, des activités de développement successives et de la situation telle qu'elle se présente actuellement. L'exposé porte notamment sur l'emploi de combustibles variés et le faible potentiel d'émission. La variété des possibilités de combustion externes offertes par ce moteur, est illustrée par un exemple. Il s'agit d'un système de propulsion pour véhicules sans phénomènes de pollution quelconques. Ce résultat est dû à l'emploi d'un nouveau type de moteur Stirling à plateau oscillant variable dont le chauffage est assuré par un dispositif rechargeable de stockage thermique. Une spécification est donnée des composants techniques et des caractéristiques de performance se rapportant à ce type d'ensemble de propulsion.

Zusammenfassung

Es wird eine allgemeine Beschreibung der Möglichkeiten des Stirlingmotors, seiner Entwicklung im Laufe der Jahre und seines gegenwärtigen Entwicklungsstandes gegeben. Die Möglichkeit, die unterschiedlichsten Brennstoffe mit einem sehr geringen Schadstoffanteil in den Abgasen anzuwenden, wird detaillierter besprochen. Als ein Beispiel für die Mannigfaltigkeit der mit diesem Motor zu kombinierenden externen Erhitzungssystemen wird ein völlig abgasfreier Automobilantrieb der aus einem neuen Stirlingmotortyp mit einem verstellbaren Schiefscheibenantrieb und einem aufladbaren thermischen Energiespeicher besteht, beschrieben. Die Leistungscharakteristik und die bisherigen Versuchsergebnisse eines solchen Antriebes werden mitgeteilt.

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1. INTRODUCTION

The gasoline engine and the diesel engine fulfil at present an important role in the modern society, especially in road transport applications. But in their present form and by virtue of their increasing numbers they begin to pose a problem for the well-being, and perhaps also in the near future, for the welfare of the society. Regarding the well-being of the people the contribution of these engines to air pollution is well known and therefore measures are already being taken to reduce this effect. The noise pollution created by internal combustion engines is probably just as important for the people but this problem has not yet received much attention. Regarding the welfare of mankind it can be said that although the gasoline engine and the diesel engine contributed quite a lot to the development of the present standard of living, the number of engines has become so large that their fuel consumption takes a large part of the total quantity of the available fossil fuel reserves. It is dangerous that the existance of the internal combustion engines is only based on the availability of crude oil and not on the availability of energy in general.

The acceptance and development of a new energy source will be strongly determined by the way it is produced and how the use of it will disturb the environment. It is clear that in those parts of the world where much coal is available, attempts will be made in the future to use synthetic fuels for conventional prime movers. It is likely that from the viewpoint of energy consumption the efficiency of the manufacturing process of high grade synthetic fuels necessary for conventional engines is not high, if the efficiency is defined as the ratio of the usable energy of the new product to the energy contained in the raw material and that necessary for the extraction of the fuel. When it is possible to burn lower grade synthetic fuels in existing or new prime movers the "efficiency" of the overall production process will be higher. In those countries that do not have coal or other fossil fuel reserves, nuclear power stations will probably be the main energy source to be supplied to the users in the form of electricity. So it can be imagined that in the future it could be very attractive when the prime mover could use energy in various forms coming from various types of energy sources.

Although it is true that the gasoline engine and the diesel engine have had and will have a great significance for the development of the standard of living of mankind, it is also true that the characteristics of these conventional engines are not optimal in the rapidly changing world. Although any other prime mover will have advantages and disadvantages the Philips Company is convinced that the potential and the characteristics of the Stirling engine meet many demands and requirements of the society, now and in the future, regarding environmental protection and the necessary flexibility and conservation in the use of energy.

2. PRINCIPLE AND POTENTIAL

The Stirling engine is a piston engine based on a closed cycle system, converting heat into mechanical power. Part of the engine is kept at a high temperature level (~750° C) by supplying heat continuously to the system through the wall of a heat exchanger, while another part of the engine is kept at a lower temperature by extracting heat from the system through the walls of another heat exchanger. By a compression of the working gas at low temperature and an expansion at high temperature, mechanical power is produced. Mechanical energy is extracted from the system by means of a rotating shaft, see Fig. 1. For more detailed information on the basic principles of the Stirling process reference is made to the relevant literature. Because of the closed cycle system the Stirling engine has characteristics that differ from those energy converters working on the basis of an open cycle such as the gasoline engine and the diesel engine. In the following, attention is given to some of these differences.

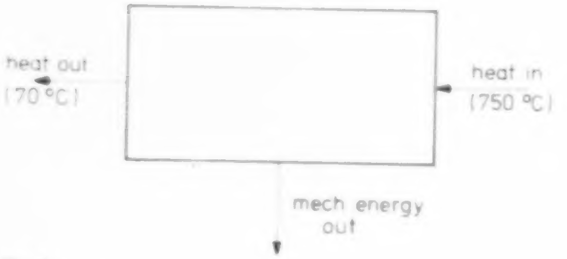

Fig. 1.
Schematic diagram of a closed power system.

a. External Heating

The external heat supply makes the engine suitable for a wide variety of heat sources without any essential modification of the engine being necessary. Apart from heating the engine by non-conventional heat sources as solar heating or heating by a radioisotope or a heat storage unit, the engine can be heated by a wide variety of fuels. All liquid fossil fuels, synthetic or non-synthetic, can be combusted in the engine under very favourable circumstances, e.g. continuous combustion, atmospheric conditions, hot walls surrounding the burner, possibility of a large air excess and of a recirculation of the exhaust.

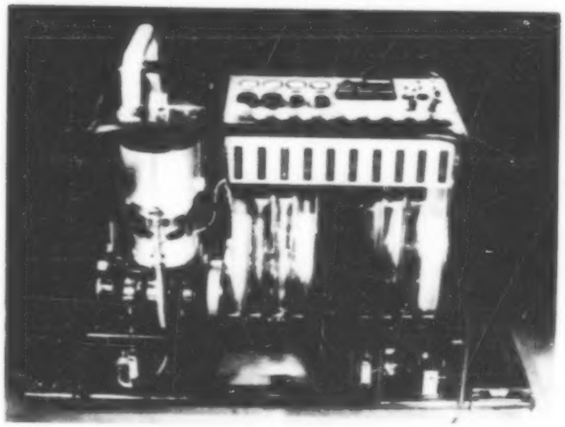

Fig. 2.
Stirling engine with generator to demonstrate its multifuel capacity. Power 10 hp; speed 3000 rpm; fuels: alcohol, various lead-containing gasolines, diesel, lubricating, olive, salad and crude oils, propane, butane and natural gas.

A unit demonstrating this potential is shown in Fig. 2. The engine in this unit can be switched from one fuel to another at any load without there being any perceptible effect on power and efficiency.

b. **Clean Exhaust Gases**
In table I some results of emission tests are given. A CVS test simulation including start up and transient operation was run with a burner sized for the 170 bhp Ford Torino car Stirling engine. Fuel and air flow to the burner were programmed based on the power requirements of the CVS-CH cycle. It can be concluded from these results that a diesel fuelled Stirling engine can easily meet the emissions limit required by law in the U.S.A. in 1977.

Table I
Results of CVS test simulator;
full scale combustor tests

Constituent	Stirling burner	U.S. Federal standard 1977
Unburned hydrocarbons	0.2	0.41
Carbons monoxide	1.20	3.40
Oxides of nitrogen	0.14	0.40

Emission projections (g/mile) of a 1972 Torino powered with a 4-215 DA Stirling engine, compared with U.S. Federal emission restrictions (CVS-75 standard for 1977).

c. **Noise and Vibration**
Because of the absence of intermittent explosive combustion, the presence of a sinusoidal pressure variation of the working medium and the facility to completely balance the mass forces, the Stirling engine is silent in operation and practically free from vibrations. The low noise level has been confirmed by measurements of the external sound level of the Stirling bus equipped with a four cylinder Stirling engine.
Noise measurements conducted on the bus according to the SAE J366 specifications during acceleration showed noise levels no higher than 68 dbA which is 10-15 dbA lower than for current buses and 7 dbA lower than the noise limit established by the Chicago Department of Environmental Control (1971) for vehicles with a gross weight of 3½ tons or more.

d. **Other Features**
Other features of importance for vehicle propulsion:
- good efficiency, also under part load, better than high compression ratio gasoline engines even before emission controls.
- specific weight equal to gasoline engines.
- wide speed range and favourable torque characteristic.
- favourable tangential-effort diagram (of importance for the driveability of the car).
- no lubricating-oil consumption, no oil changes.
- insensitivity to dust in the combustion air.
- reliable starting under all conditions.
- relatively large amount of heat rejected by the cooling water.
- efficiency and power decrease with increasing cooling-water temperature and decreasing heater temperature.
- engine not reversible.

3. STATE OF THE ART

Engine Development

Research into the Stirling engine, formerly know as the hot-air engine, was started as early as 1938. At that time the company was looking for a heat-driven electric generator with multifuel capability, low noise and long life potential for radio receivers and similar equipment. Improvements in radio tubes and above all the advent of the transistor virtually removed the original reason for developing the engine. On the other hand all the studies had provided deeper insight into the potential of larger engines for many applications.

A distinction can be made between displacer type Stirling engines and double acting type Stirling engines. Many types of drive systems can be designed for both types of engines but only two have been developed and intensively tested.

In a displacer type Stirling engine there is one cylinder and there are two pistons which have a certain phase difference in their movement in relation to each other, see Fig. 3. The working gas is forced to flow to and fro in the heat exchangers – heater, regenerator, and cooler – by the piston at the top, the displacer piston. For producing power the displacer piston must be in the right phase in relation to the piston at the bottom, the working piston. The necessary phase difference between the working piston and the displacer piston is realized by the rhombic drive system, see Fig. 4. A single cylinder rhombic drive Stirling engine can be exactly balanced. Some single cylinder rhombic drive Stirling engines of different power

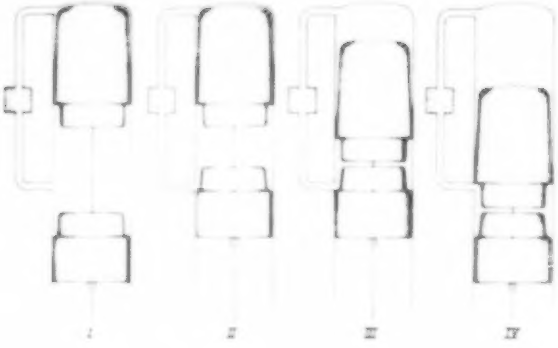

Fig 3

Diagram of the displacer type Stirling engine

I. Piston in lowest position; displacer in highest position; all the gas is contained in the cold space.

II. The displacer has remained in the highest position, the piston has compressed the gas at the low temperature.

III. The piston has remained in the highest position; the displacer has pushed the gas via cooler, regenerator and heater into the hot space.

IV. The hot gas has expanded, displacer and piston have together reached the lowest position. Thereafter, with the piston stationary, the displacer pushes the gas via heater, regenerator, and cooler into the cold space, so that position I is reached again.

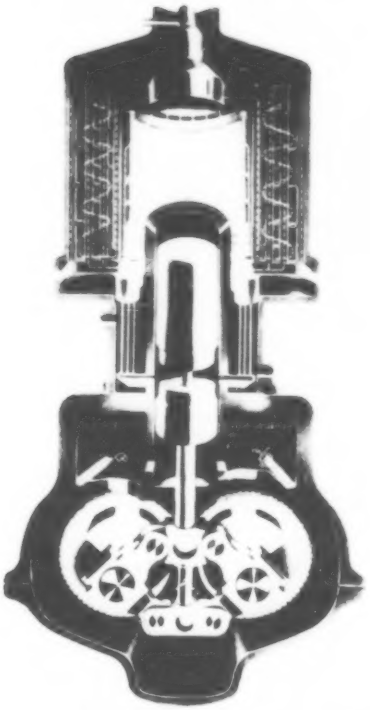

Fig 4

Section through a single cylinder displacer type Stirling engine with rhombic drive. In the centre are the cylinder, piston and displacer. Below is the crankcase with the rhombic drive which governs the movement of the piston and displacer with respect to each other. The part above the cylinder is the heater head surrounded by a preheater. The air required by the burner enters the preheater at the bottom and passes through a channel heated by the exhaust gases before reaching the flame. The exhaust gases escape at the top. It is equally possible to perform the heating by other methods.

output have been tested extensively in some applications for instance in a generatorset (Fig. 5) in a motor yacht (Fig. 6) and in a garden tractor (Fig. 7). With these applications it was possible to demonstrate the low noise level and the possibility of a perfect control of a Stirling engine. In a full load endurance test of 10.000 hours its suitability for long life applications has also been demonstrated.

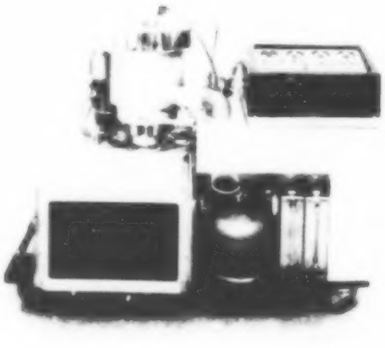

Fig. 5.

4 kW generatorset with a single cylinder displacer type Stirling engine with rhombic drive.

Fig. 6.

The motor yacht 'Johan de Witt', equipped with a 30 bhp single cylinder displacer type Stirling engine with rhombic drive.

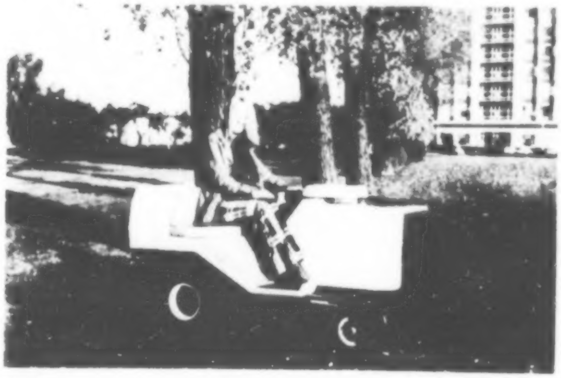

Fig. 7.

A garden tractor equipped with a 10 hp single cylinder displacer type Stirling engine with rhombic drive.

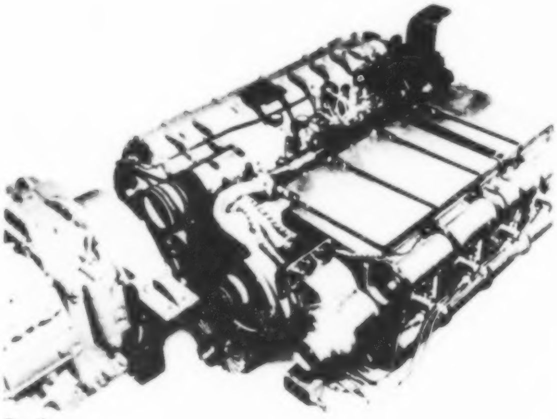

Fig. 8.
A four cylinder displacer type Stirling engine with rhombic drive designed for 200 hp.

Fig. 9.
The Philips Stirling bus equipped with a four cylinder displacer type Stirling engine with rhombic drive.

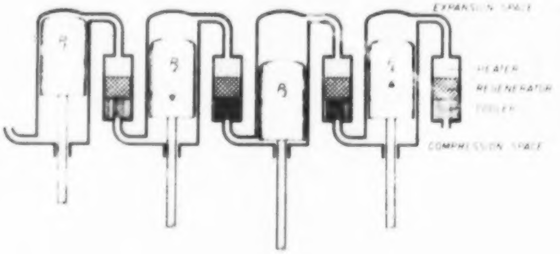

Fig. 10.
Diagram of the double-acting type Stirling engine. Principle of the double-acting engine. There is a hot space – expansion space – at the top and a cold one – compression space – at the bottom of each of the four cylinders shown. The hot space of a cylinder is connected to the cold through a heater, a regenerator and a cooler. The pistons Pn of the cylinders move with a suitable phase shift between them. In the case of four cylinders, as shown here, this shift is 90°.

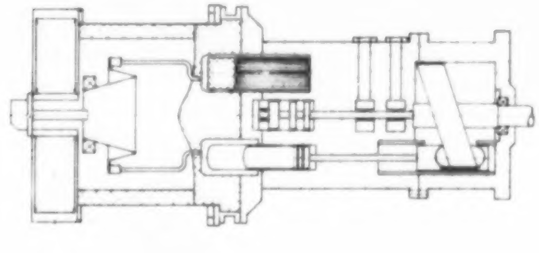

Fig. 11.
Schematic diagram of a four cylinder double acting type Stirling engine with swash-plate drive. One of the four cylinders and one of the four cooler-regenerator units are shown in cross-section. In these engines the movement of the pistons is transmitted to the main shaft by a swash-plate.

It is difficult to design an integrated multicylinder displacer engine. It becomes in fact a series of separate single cylinder engines and simplification cannot be attained.
An example of a four cylinder displacer type Stirling engine with rhombic drive is shown in Fig. 8. This engine has been mounted into the Philips Stirlingbus, although this engine was not specially designed for road vehicle application, see Fig. 9. With the construction of this engine a first goal was achieved in designing and building a Stirling engine which had a specific power equal to the diesel engine.

Through the research and development work with these displacer type Stirling engines many technical problems were solved and as a result, work on an old concept, the double acting Stirling engine, was resumed. The double acting Stirling engine is already an integrated concept which offers a simple, light weight and compact engine suitable for many applications. In the double acting engine three or more separate Stirling cycles and an equal number of pistons and cylinder can in principle be distinguished, see Fig. 10.

Many drive configurations can be designed for double acting Stirling engines but in 1967 after an extensive study Philips opted for a drive system where the reciprocating movement of the pistons is converted into a rotating movement by a tilted plate a so called swash-plate, as eminently suitable for a double acting Stirling engine. In a research and development programme the potential of this swash-plate drive was further explored and very good performance characteristics were attained. In Fig. 11 a scheme of a double acting four cylinder Stirling engine with swash-plate drive is shown. In this engine the heaters of the four cylinders are arranged to form one cylindrical heater cage. All the heating sources can then be replaced by one common heat source and a fully integrated design is possible. Three swash-plate engines, each with a nominal power of 60 hp have been designed and tested, see Fig. 12. During this programme their functional behaviour was investigated and an extensive measuring programme executed. It has been shown that the theory and the measurements come very close. They are currently being used to test components for the power control and air/fuel control for the 170 bhp Stirling engine to be mounted in a Ford Torino car, Fig. 13.

This last engine is now undergoing dynamometer tests. With the construction of this engine a second goal was achieved in designing and building a Stirling engine which had a specific power equal to the gasoline engine.

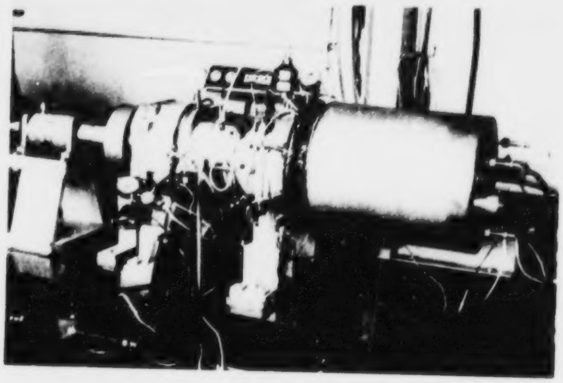

Fig. 12.
A 60 hp four cylinder double acting type Stirling engine with swash-plate drive on the test bench.

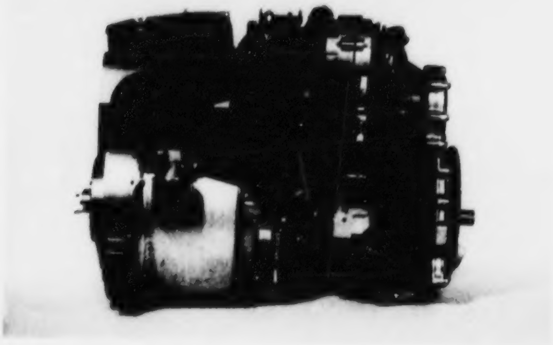

Fig. 13.
A 170 bhp four cylinder double acting type Stirling engine with swash-plate drive to be mounted into a Ford Torino car.

Parallel Activities
Alongside the research and development work aimed at making the Stirling engine itself attractive for road vehicle application other activities which help to support this purpose or to broaden the application potential of the engine have been studied. For example a compact radiator has been developed to reject the heat in the cooling water. Furthermore, because of the Stirling engines unique characteristic of only demanding energy in the form of heat at an appropriate temperature level, much attention has been given to the study of unconventional heat generation and to the transportation of heat so developed to the heater head of the engine. Heat pipes have been especially developed for this latter purpose and form an integral part of the development group task.

Compact Radiator
In a Stirling engine that part of the supplied heat that has to be rejected in the cooling water is greater than for conventional engines. Furthermore it is desirable to reject the heat at a temperature level as low as possible. Therefore a compact heat exchanger has been developed in order to obtain a sufficiently small radiator for vehicle application. The new design is based on a finer fin structure and thinner core than present in conventional radiators, while by the folded shape the radiator is not fouled by dust or flies etc. and has a smaller frontal area than a conventional radiator for the same heat rejection, see Fig. 14. Tests with a car have been made to compare the fouling of a conventional radiator and the new Philips radiator. After 15.000 km driving the fine fin structure of the new radiator was not clogged. All dirt had been collected at the rear in the V-form of the structural components from which the radiator has been built up. The conventional radiator showed quite a lot of dirt in its fin structure. A radiator designed for testing on a 100 hp motor cycle is shown in Fig. 15.

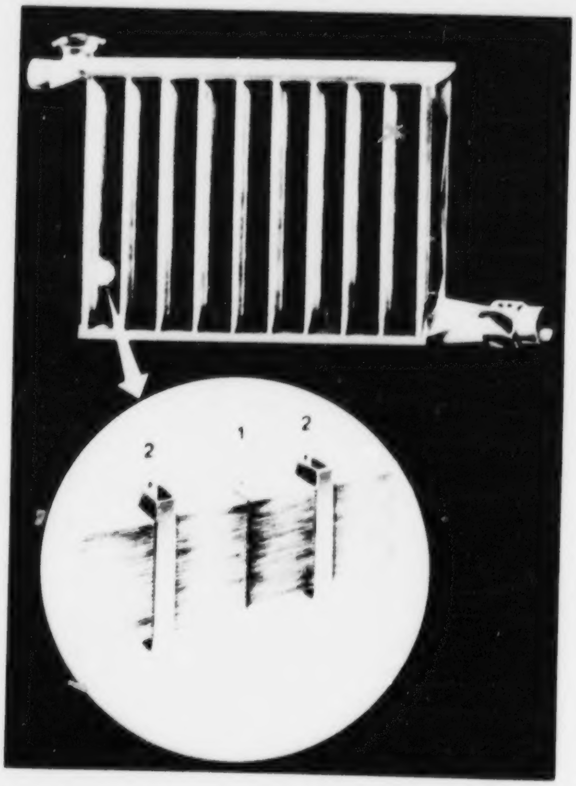

Fig. 14.
View of the folded front radiator: 1-fins; 2-cooling medium ducts.

Heat Pipe Heat Transport System
In principle a heat pipe consists of a hermetically sealed chamber, the inside walls of which are provided with a lining of porous material in which a liquid is absorbed by means of capillary forces. The simplest form is a sealed pipe, Fig. 16.

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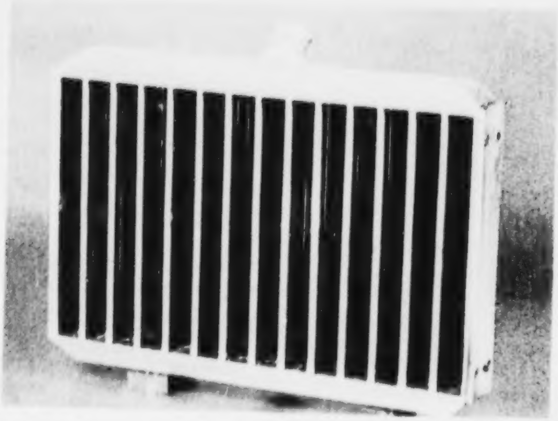

Fig. 15.
A Philips folded front radiator, designed for testing on a 100 hp motor cycle.

For the temperatures of interest for the Stirling engine (700 to 800°C) sodium is a suitable transport medium. On local heating of the wall, part of the sodium evaporates, absorbing heat. On account of the difference in pressure the vapour flows to the colder area and condenses on the unheated surfaces, giving off the amount of heat previously absorbed. The liquid thus formed flows back again, under the influence of capillary forces to the area of evaporation. Thus a cycle is set up in which sodium goes successively through the vapour and the liquid phase and in which large amounts of heat can be transferred with very slight differences in temperature. The heat pipe system can in principle be regarded as a transformer of the heat flux density. For example a large area can be heated with a low heat flux density and the amount of heat taken up can then be released at a high heat flux density, during condensation, to a relative small surface. This property is precisely what is needed in the heating of the Stirling engine. In Fig. 17 a photograph is shown of a 30 hp Stirling engine operating on a sodium evaporation and condensation system. Sodium evaporates from a wick structure as in a heat pipe. The condensate in this case is returned through a separate tube by gravity forces.

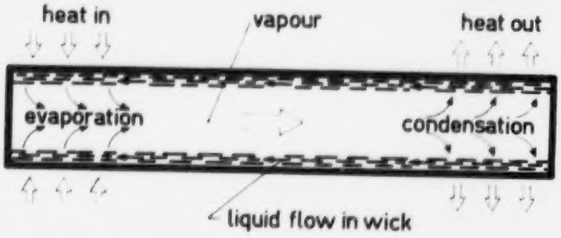

Fig. 16.
Schematic cross-section of a heat pipe. The inner wall is lined with porous material. If one of the ends (here on the left) is heated, then the heat transfer medium (here sodium) melts and evaporates. The vapour flows to the cool end (right) and condenses there, during which process heat is given up. The condensed sodium flows back under the action of capillary forces in the porous lining to the warm end. Between the places where the pipe takes up and gives up the heat it is surrounded by a layer of insulating material.

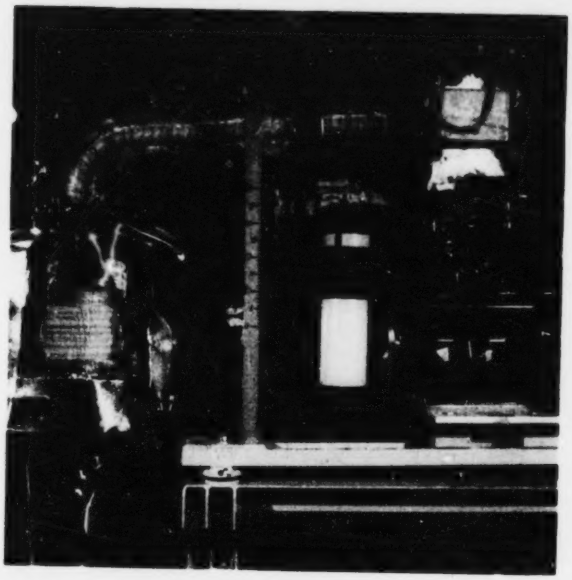

Fig. 17.
A 30 hp single cylinder displacer type Stirling engine with rhombic drive running on a modified heat pipe system. In this case the heat pipe system is electrically heated, simulating a non-conventional heat source such as a heat accumulator, metal combustion heat source or a radioisotope.

Heat Accumulator

As an example of the activities in the field of unconventional heating systems a so called heat accumulator has been developed. Essentially a heat accumulator consists of a container which is filled with a material capable of absorbing and releasing large amounts of heat. This heat can be given up to the heater of the Stirling engine for example via a system of heat pipes. Most of the experiments have been done with lithium-fluoride as the heat-accumulation material and what follows will be restricted to that material in spite of the present availability of much cheaper materials with practically the same properties.

Lithium fluoride is chemically a very stable salt with a melting point of 848°C, a heat of solidification of 250 kcal/kg, a mean specific heat of 0.56 kcal/kg°C between 550°C and 848°C, a density at 870°C (liquid) of 1.79 g/cm^3, and a density at 700°C (solid) of 2.64 g/cm^3. If the heat of solidification and the sensible heat obtained on cooling to 550°C are passed to the engine, account being taken of the efficiencies corresponding to these temperatures, a specific mechanical energy of about 200 Wh per kilogramme of lithium fluoride is found, see Fig. 18.

In order to transport the heat from the accumulator to the engine, use is made as already mentioned, of a system of heat pipes, in particular of their property of being a transformer for the heat-flux density. The thermal conduction of solidified LiF is not very high, so that a

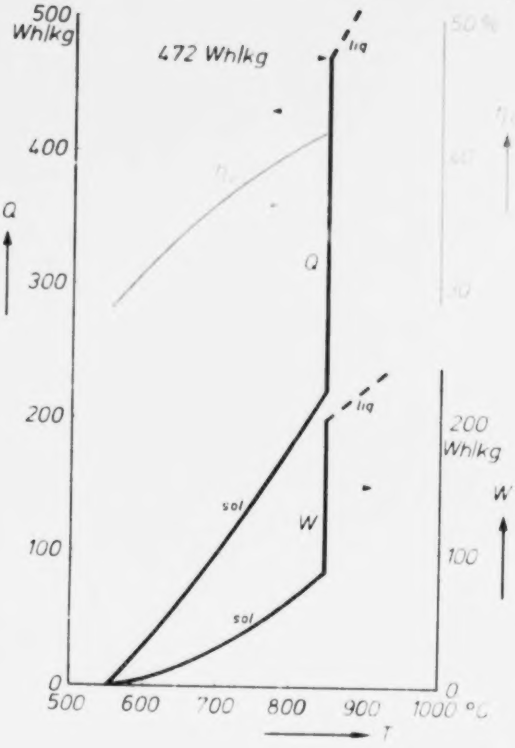

Fig. 18.
The energy content Q per kilogramme of lithiumfluoride as a function of the temperature T. At 840°C the salt melts, and the (large) heat of fusion is taken up (vertical part of the curve). When all the lithiumfluoride has melted, Q amounts to 472 Wh/kg. W is the mechanical energy obtainable from Q. η_t is the conversion efficiency.

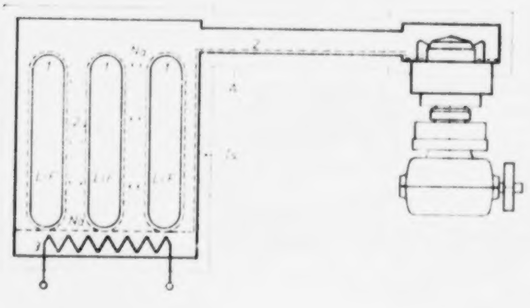

Fig. 19.
Schematic representation of a Stirling engine (right) connected via a heat pipe to a heat accumulator (left). 1 closed cells (elements) filled with LiF. 2 porous lining. 3 electric heater. Is insulation. A isolating valve in heat pipe. During charging, heat is supplied until all the LiF has melted. The walls of the elements then act as the cold end of a heat pipe and the electric heater as the hot end. When A is open, the elements form the warm end of the heat pipe which connects the accumulator to the engine (arrows).

relatively large wall surface with a small heat-flux density is necessary in order to avoid an excessive temperature gradient in the solidified salt.

Fig. 19 shows schematically an experimental set up of heat accumulator, heat pipe system and Stirling engine.

The heat accumulator actually consists of an enclosure containing small thin-walled sealed elements filled with lithium fluoride.

In the liquid state the salt occupies practically the whole volume, [illegible] small volume above the molten salt being occupied by argon at a pressure such that, when the salt solidifies, there is always a slight overpressure inside the element to prevent it from collapsing. The broken lines in Fig. 19 indicate the porous lining through which the sodium, the heattransfer medium, flows back as liquid to the site of evaporation. The operation of the system is as follows: let there be a kind of valve at A which seals off the connection between the accumulator and the engine. If the bottom of the large container is electrically heated, sodium evaporates and condenses on the elements, where the heat of condensation is given up. The liquid sodium is led back to the bottom by the porous lining.

Fig. 20.
A radiograph of one element of a heat accumulator, surrounded by a heat pipe. The salt (light region) is here in the solid state.

This process can go on until all the salt in the elements has been melted, which is indicated by an increase in the rate at which the temperature rises. The heat accumulator is now "charged" and the supply of electrical energy can be shut off. To start the engine the "valve" at A is opened, so that the sodium vapour condenses on the heater tubes and the liquid flows back again to the outer surface of the elements, which now constitute the evaporating part of this heat pipe system. Fig. 20 is a radiograph of a test element surrounded by a system of heatpipes. The salt is in the solidified state. Fig. 21 shows a test set-up of the entire system in accordance with Fig. 20. It is a 70 kWh heat storage unit constructed for operation with a 7.5 kW Stirling engine. On this unit about 1000 operational hours have been obtained.

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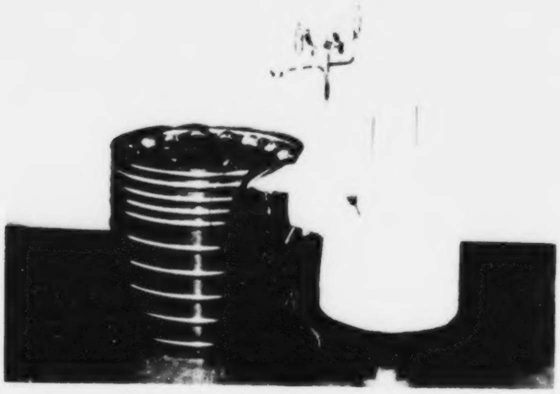

Fig 21.
Test set-up in accordance with fig. 20. On the left, with cover removed, the heat accumulator. The upper ends of the elements are just visible.

Fig. 22.
A small generator-set with a Stirling engine driven by the heat from a brazier. The Stirling engine is connected to the heat source by a heat pipe. This method of heat transmission is of considerable interest for vehicle engines.

4. A ZERO POLLUTION AUTOMOBILE PROPULSION UNIT

Introduction

The "multifuel capability" of a vehicle engine can only be realized if the fuel is truly portable and can be burnt simply without unacceptable air pollution. For example it is almost unthinkable to carry pieces of coal in an automobile for fuelling purposes even though during the last world war gasification of coal in cars has been applied. However it is extremely inconvenient and it is likely that todays stringent exhaust emission requirements cannot be fulfilled. In principle the Stirling engine can also run on coal as shown in Fig. 22.

It is perhaps more conceivable to consider that in countries where energy is generated in many forms, instead of having gasoline and diesel tank stations, so called "heat stations" can be attractive. The "heat" is then supplied to a car with a heat accumulator which in turn powers a Stirling engine. The advantage of such "heat stations" is that the fuel can be burnt under much more favourable conditions than in an automobile thereby contributing to less air pollution. Moreover, where sufficient electricity is available, it is possible to recharge electrically the heat accumulators of automobiles which are driven by "heat". In this case the less efficient use of the primary energy has to be considered. On the other hand "off-peak" electricity can be used resulting in a more efficient use of the primary converter especially when this is a nuclear reactor.

For the acceptance of automobiles with heat engines and accumulators it is of course important to ensure an adequate performance of these vehicles. The term "adequate performance" is difficult to define since it depends on many circumstances for example personal choices, legislation etc. In the following some material is presented on the design of a commuter or city car with adequate performances based on a Stirling engine with heat accumulator.

Total layout

As study object a front wheel drive automobile has been taken of the sort typified by the European models Peugeot 104, Renault 5TL, Fiat 127 and the Japanese Datsun 100A, since these represent the latest trends in design of commuter cars.

Figure 23 shows an installation in such a typical European commuter car. The heat storage unit is located beneath the passenger compartment and heat is transmitted from it to the engine through a heat pipe heat transport system. The system contains only a small amount of sodium. The heat transport to the engine can be switched on and off by monitoring a mechanical sodium vapour valve as shown in Fig. 19 or by using a system where an inert gas is being introduced in or withdrawn from the system. Also a good thermal insulation is required. A multifoil evacuated insulation made from metal with a total thickness of some mm will be used. A getter made from a metal hydride can be used to maintain the vacuum.

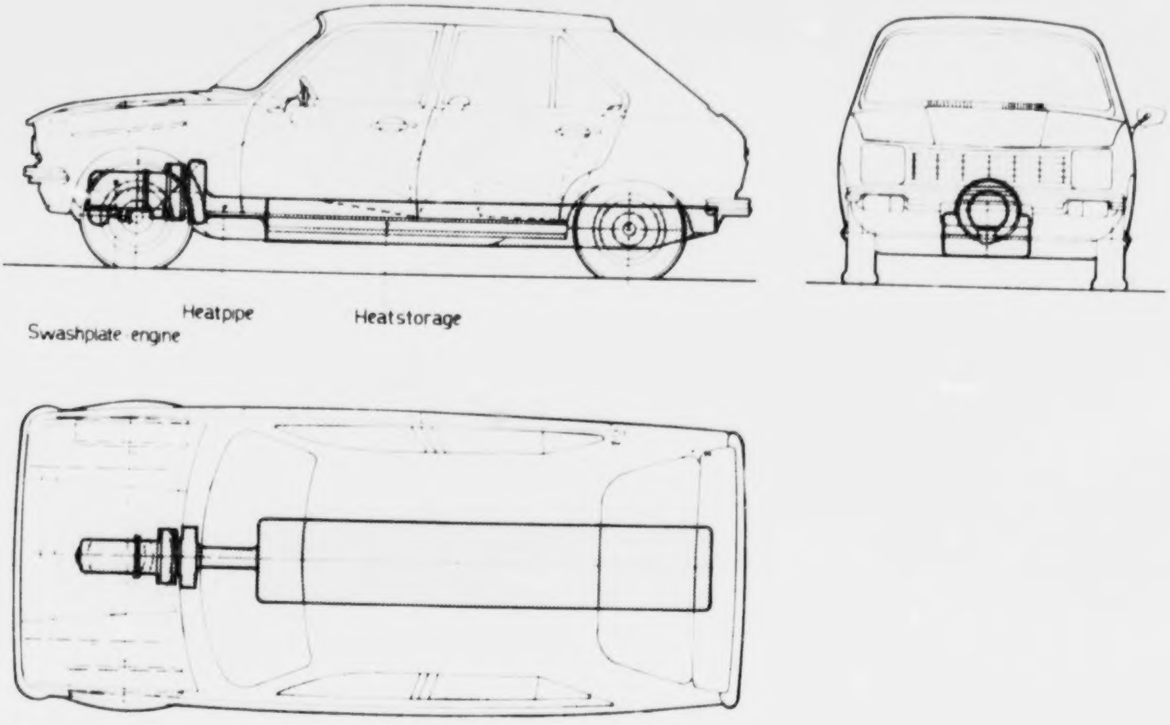

Fig 23
Schematic view of a commuter car equipped with a Stirling engine, heat storage unit and heat transport system.

Putting:

Maximum allowable weight	1160 kg
Weight of automobile without engine and gasoline tank	600 kg
Maximum weight of passengers plus luggage	300 kg

Results in:

Weight available for heat accumulator and Stirling engine	260 kg

In the following, performance data are based upon the automobile plus two passengers, that is a total weight of 1010 kg.

A nominal maximum speed is assumed of 110 km/hr. Taking the frontal area of the automobile as 2.1 m² and assuming a drag coefficient of 0.3 a value of 15 HP (11 kW) is obtained for the power necessary to overcome the aerodynamic resistance of the vehicle. The rolling resistance of the automobile is calculated to be 10 HP (7.3 kW) giving a total of 25 HP (18.4 kW) necessary to supply to the wheels of the vehicle to achieve the nominal maximum speed of 110 km/hr. With these figures in mind, a Stirling engine has been selected with a nominal output equal to 20 kW. Based on this power output the heat exchangers of the engine have been optimized.

There will always be a discrepancy between the engine power necessary to achieve maximum speed and that necessary to have good acceleration. Even if the above named engine of 20 kW output had a drive mechanism with a purely hyperbolic torque-engine speed characteristic then 80 km/hour could only be achieved in 20 seconds. This could perhaps be acceptable in Europe but in the U.S.A. it would not fit in the pattern of the traffic. Therefore a new concept of a Stirling engine has been developed which overcomes this difficulty and which at the same time by virtue of a variable swashplate mechanism giving a large variation of the torque with engine speed, also does the job of the automatic transmission making this latter component unnecessary.

Variable Swash-plate Engine

When the size of a Stirling engine is fixed in connection with the required specific power (related to the weight and/or volume) the dimensions of the heat exchangers can be optimized with respect to high efficiency at a particular engine load e.g. maximum power. The engine load is determined by the mean gas pressure in the engine and the engine speed. Assuming for instance that the mean pressure is held constant then the power is wholly determined by the engine speed. Concerned for the time being to design an engine with the desirable hyperbolic torque-engine speed characteristic (constant power condition) so that the automatic transmission can be omitted, the following train of thought can be followed.

In the case of constant mean pressure, the engine power is approximately half of the maximum power at half of the maximum engine speed. The heat exchangers in this instant are only working under half load condition, since the mass flow through them is a half also. If it is desirable to have the full nominal power of the engine available also at half of the engine speed, the heat exchangers can fulfil this task provided the heat supply and the heat rejection can be guaranteed.

In principle, there are several ways in which the mass flow through the heat exchangers can be kept constant and having the full power of the engine available independently of the engine speed, firstly for instance by variation of the mean pressure in the engine and secondly by varying the swept volume of the piston.

Variation of the mean pressure.
The mean pressure in the engine at full load is assumed to be 200 atm. At a half of the maximum engine speed the pressure must be 400 atm. in order to maintain nominal maximum power output. Because it is desirable to exceed the nominal maximum load of the engine for brief periods during acceleration, even higher pressures are required. Because of technical reasons this system becomes unacceptable.

Variation of swept volume.
Now the variation of the swept volume for controlling the power will be discussed. It appears that for a particular constant power output, the necessary variation of piston stroke with engine speed is much smaller than the necessary linear variation of the system pressure as previously discussed. This is due to the fact that the variation of swept volume also influences the dead volume of the engine. Furthermore by applying a variable swept volume control it is easy to obtain more than the nominal maximum power output, although this is then coupled with larger flow losses in the system and thus a somewhat lower efficiency. The control of torque by variation of the piston stroke is interesting since the size of a Stirling engine is mainly determined by the size of the heat exchangers, and not by the pistons and drive mechanism. For instance the 170 BHP of the Ford Torino Stirling engine is obtained with a total swept volume of $2 \times 860\ \text{cm}^3$ (double acting). Fig. 24 shows schematically the new concept.

A change of the angle the swash-plate makes with the mainshaft causes a variation in the piston stroke and hence in the swept volume of the engine, influencing the power output of the engine. On the swash-plate a torque from the gas forces is acting which tries to make the angle α zero. This torque is a maximum at the maximum angle of 22° and reduces to zero at zero degrees. The torque is practically independent of engine speed. To change the swash-plate angle α from 6° to 22° in a short time (say 0.6 sec) requires about 1 HP. Therefore this operation is performed hydraulically and combined with a compensating mechanism using a spring with a so called negative spring characteristic in order to minimize the power necessary for the adjustment of the swash-plate angle. All the forces acting on the swash-plate are now completely balanced for every swash-plate angle, thereby allowing easy hydraulic movement of the swash-plate, see Fig. 25.

As shown in Fig. 24, this relatively small engine has a pressurized crankcase in which the hydraulic clutch and the gearwheel with fixed reduction are housed, thereby allowing a simple piston rod seal to be used. The engine

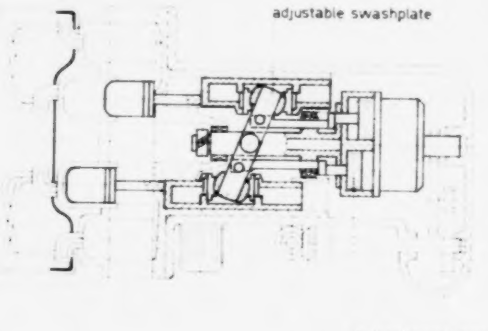

Fig.24.
Schematic diagram of a four cylinder double acting Stirling engine with variable swash-plate drive. With the hydraulic pistons the position of the swash-plate can be adjusted.

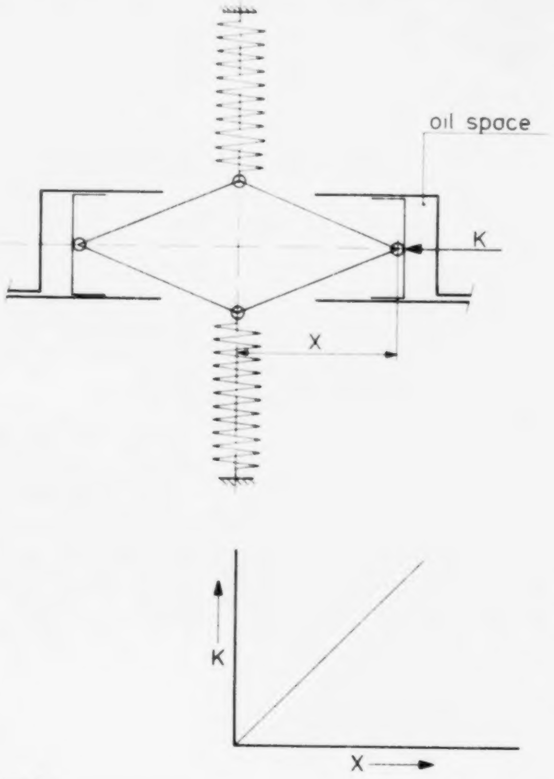

Fig. 25.
The negative spring mechanism. In this compensating mechanism the spring forces generate a certain pressure in the oil space. This space is connected with the hydraulic pistons, which control the position of the variable swash-plate. The gas forces from the Stirling cycles acting on the swash-plate are always in balance with the hydraulic forces from the compensating mechanism. Thus variation of the position of the swash-plate requires in principle no energy. The compensating mechanism must have a "negative" characteristic: K, which is the force exerted by the oil on the pistons, decreases when the piston moves in the direction of K (hence decreasing X).

is sealed by means of a rotating seal on the output shaft. The differential gear is placed outside the engine crankcase.

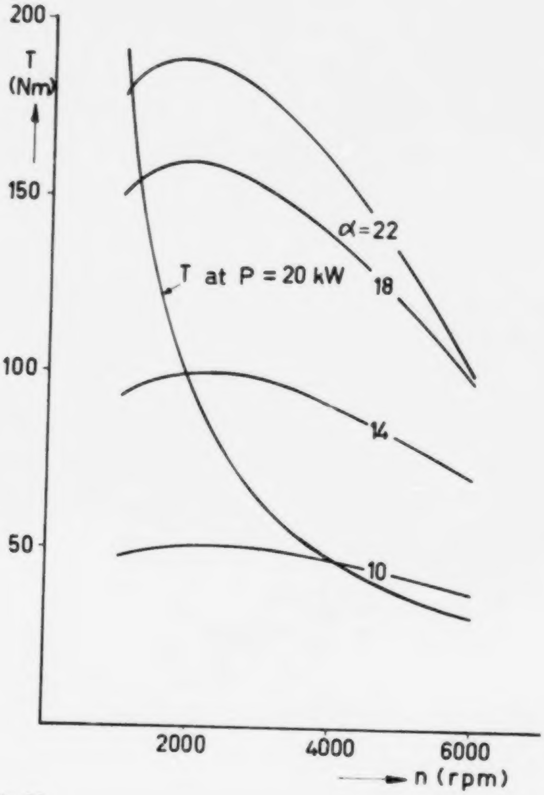

Fig. 26.
Torque versus r.p.m. for various angles of the swash-plate and constant power.

Fig. 26 illustrates the calculated characteristics e.g. torque versus engine speed of the above mentioned automobile inclusive of the mechanical losses and inclusive of the engine auxiliaries. However, when the heat source is assumed to be a heat accumulator, these auxiliaries comprise only the oil lubrication pump, water pump, radiator fan and alternator. It has to be emphasised that the variable swash-plate engine can also be combined with a conventional burner heat source in case the auxiliaries are designed for the maximum possible power output of the engine.

Acceleration and Range Performances

At a nominal power output of 20 kW the hyperbolic torque-engine speed characteristic of Fig. 26 shows a variation in torque with engine speed of more than 1 to 4 for a change in swash-plate angle from 6 to 22°. This torque variation is normally considered as ideal to fulfil the performance requirements so that a transmission unit and torque converter are no longer necessary. From Fig. 26 it can also be concluded that for acceleration more than three times of the nominal power output is available provided that the necessary heat can be supplied.

With the heat accumulator as heat source and the heat pipe as heat transport system the heat supply is always guaranteed. In this case the auxiliaries are not the limiting factor. With the available power output at a swash-plate angle of 22° the following acceleration times have been calculated:

0 – 30 km/h	2.2 sec
0 – 60 km/h	6.4 sec
0 – 90 km/h	10.2 sec
0 – 110 km/h	13.8 sec.

These figures are comparable to those of modern present day passenger cars.

As already shown before 260 kg is available for the engine, the heat storage material and the container and heat pipe system. The weight of the engine is estimated to be 60 kg while for the container and heat pipe roughly 45 kg is necessary. This means that taking pure Lithium-fluoride and a temperature interval of 850 to 550 °C a heat storage capacity for the car is available of 72 kWh, meaning 155 kg or 85 dm^3 of storage material based on Lithium-fluoride. Allowing for heat losses a mechanical energy of about 23 kWh can be obtained. With this mechanical energy storage the following ranges are possible:

Range cruising at maximum speed	130 km
Range cruising at 70 km/h	300 km.

These ranges are sufficient for the daily use of a commuter car.

5. CONCLUSION

Besides the good efficiency of the Stirling engine the property of the external heating has been emphasized especially in view of the coming shortness of crude oil. External heating means the possibility of using all kinds of fuels if they are controllable and combustable with low pollution. In the case where fuels are available but are complicated to burn in a pollution free manner, the suggestion has been made to have stationary "heat stations" for vehicle propulsion, which can for instance "load" a city car provided with a Stirling engine and a heat storage device. Laboratory tests have shown that such a zero pollution city car can have a very acceptable range and other performance characteristics.

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Advanced Development on Stirling Engines at M W M

Fortgeschrittene Entwicklung an Stirlingmotoren bei M W M

Dr.-Ing. F. A. ZACHARIAS

Entwicklungsgruppe Stirlingmotor M.A.N.-M W M
D 8900 Augsburg 1, Stadtbachstr. 1

A comparison of the sizes of the Stirling and Diesel engines shows that horsepower for horsepower the two engines take up the same space, but the Stirling engine makes greater demands on the cooling system. Reasonably priced Stirling engine elements of M.A.N.-M W M design are described and the possibility of series production using the modular principle explained. A new form of power control is also treated.

Une comparaison des tailles du moteur Stirling et du moteur Diesel fait ressortir que, pour une puissance semblable, les deux moteurs ont le même encombrement, mais que le moteur Stirling exige plus de l'installation de réfrigération. On abordera la question des éléments d'un prix avantageux du moteur Stirling type M.A.N.-M W M, ainsi que la possibilité d'une série de fabrication selon le principe modulaire. Un nouveau système de régulation de puissance sera présenté.

Ein Größenvergleich zwischen Stirlingmotor und Dieselmotor ergibt bei gleicher Leistung gleichen Raumbedarf beider Motoren und höhere Anforderungen des Stirlingmotors an die Kühlanlage. Es werden kostengünstige Stirlingmotor-Elemente der Bauart M.A.N.-M W M und die Möglichkeit einer Baureihe nach dem Baukastenprinzip erläutert. Ein neues Leistungsregelsystem wird vorgestellt.

Of all the heat engines working on external combustion processes, or, to generalize, with external heat input, the Stirling engine can be classed as one of the most significant objects of development.

This engine is highly efficient and maintains its high efficiency even under partial load. Its very low level of emission of noxious substances in the exhaust and of noise pollution is inherent in its design. Data on emission levels have been published more than once, including figures from measurements carried out by M.A.N.-M W M /1/ [+] and Philips using exhaust-gas recirculation /2/.

The compatibility of the Stirling engine with the environment, which is outstanding in comparison with other heat engines, calls for an intensive development follow-up, with which M.A.N. and Motoren-Werke Mannheim, M W M, are jointly forging ahead.

Ever since it has been running in the research laboratories, the Stirling engine has been manifesting its outstanding properties:

Low exhaust gas pollutant emission level
Very low noise level
High efficiency even under partial load
Capacity to burn all types of fuel (from petrol to heating oil without modifications to engine)
Advantageous torque characteristics

Against these properties of the Stirling engine stand the following problems, which are well known amongst experts:

1. Size
2. Weight
3. Cost
4. Control

1. Size

Development of the Stirling engine has reached a stage where it

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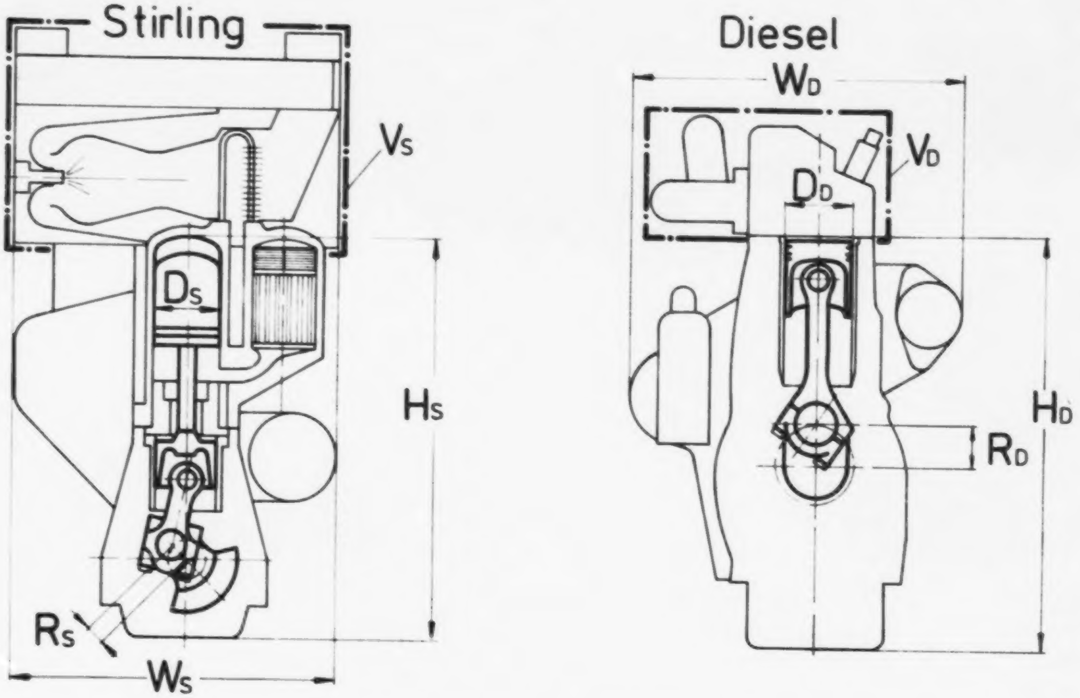
[+] Numbers given between oblique strokes refer to the bibliography at the end of this paper.

is now possible to pass certain judgments as to its size; these are given below, Fig. 1.



$H_S \approx 25 \times R_S$	Height of crank gear	$H_D \approx 10 \times R_D$
$L_S \approx 1.6 \times D_S \times Z$	Length of crank gear	$L_D \approx 1.4 \times D_D \times Z$
$W_S \approx W_D$	Width of crank gear	W_D
$p_S \approx$ 18 bar (at 110 bar m.p.)	BMEP	$p_D \approx$ 8 bar
$V_S \approx 0{,}002\ m^3/kW_{eff}$	Volume combust. syst.	$V_D \approx 0{,}001\ m^3/kW_{eff}$

Fig. 1. SIZE PROPORTIONS OF STIRLING AND DIESEL ENGINES

First of all, the running gear of the double-acting Stirling engines of M.A.N.-MWM development projects and usual Diesel engine running gears should be considered. For the crank gear dimensions mean relationships are obtained for such factors as height H as a function of the crank radius and length as a function of piston diameter and of the number of in-line cylinders Z.

The crosshead running gear of the considered Stirling engine requires, if allowance is made for the seals and high pistons (needed to reduce temperature gradient) an overall height of approximately 25 times the crank radius; this is in contrast with the height of rhombic running gear, where $H \approx 32 \times R_S$ and Diesel engine running gear with 10 times the crank radius. Even for swash plate running gear a height of $H \approx 25 \times R_S$ has been ascertained.

The varying sizes of oil sump spaces shown in Fig. 1 are conspicuous. The particularly low loads imposed on the oil in the Stirling engine permits small oil quantities to be used.

Cylinder spacing in the Stirling engine is 1,6 x D as opposed to 1,3 to 1,4 x D in the Diesel engine. The greater spacing in the Stirling engine is, as a function of the piston diameter, to be attributed to the fact that the cylinders must be designed for even higher pressures and also divisible between the hot and cold regions for the reasons of assembly and materials economy.

The width of the engine shows that with the inclusion of the auxiliary units it can be expected that the Diesel engine and the Stirling engine both have the same width.

The brake mean effective pressure in non-turbocharged Diesel engines is $p_D = 8$ bar - and in the Stirling engines built so far p_S is 18 bar if helium is used as the working medium and the mean cycle pressure is 110 bar.

The combustion system accounts for a considerable part of the size of the Stirling engine. It consists of the combustion chamber, the heat-input heat exchanger of the internal Stirling cycle (heater) and the air preheater. If the volumes of the component parts of the combustion system are added up and related to the effective power output of the engine, it is possible to get a representative value of the specific combustion system volume. An average value of this specific volume achieved from different Stirling engine types is $V_S \approx 0{,}002 \ m^3/kW$.

By way of comparison the volumes of the following parts of the Diesel engine have been adduced: cylinder heads, air and exhaust gas manifolds and silencers. Allowing for certain amount of scattering this comparative volume of non-turbocharged vehicular Diesel engines can be expressed as up to $V_D \approx 0{,}001\ \mathrm{m^3/kW}$.

For the following comparative assessment it should be assumed that the Stirling running gear has the same size as that of the Diesel engine. The question then arises of under what conditions (speed and BMEP) the Stirling crank gear must run in order to attain the same output as the Diesel engine, Fig. 2.

Stirling		**Diesel**
$H_S \approx 25 \times R_S$	Height	$H_D \approx 10 \times R_D$
$L_S \approx 1{,}6 \times D_S \times Z$	Length	$L_D \approx 1{,}4 \times D_D \times Z$
$W_S \approx W_D$	Width	W_D

1. Requirement: Same crank gear length (same number of cylinders

$$D_S = \frac{1{,}4}{1{,}6} \times D_D = 0{,}875 \times D_D$$

2. Requirement: Same crank gear height

$$R_S = \frac{10}{25} \times R_D = 0{,}4 \times R_D$$

3. Requirement: Same output

$$P_S = C_S D_S^2 R_S n_S p_S = P_D = C_D D_D^2 R_D n_D p_D$$

with $C_S = 2 \times C_D$

yields $n_S p_S = 1{,}63\ n_D p_D$ (1)

Assumption : $n_S = (\frac{1}{2} \dots \frac{2}{3}) \times n_D$ (2)

yields $p_S = 3{,}27 \dots 2{,}45 \times p_D$ (3)

$p_S = 26 \dots 19$ bar

These mean effective pressures are achievable by mean cycle pressures of

$p_m = 110 \dots 160$ bar

Fig. 2. BMEP OF EQUIVALENT STIRLING RUNNING GEAR

From same size and power output of both engines one arrives at equation (1). Assuming that a Stirling engine using helium as the working medium must run more slowly than a Diesel, equ.(2), if high efficiency is to be maintained, the relationship in equ.(3) is obtained.

The resultant brake mean effective pressures of 19 to 26 bar are normal for Stirling engines, i.e. they are attained by average helium cycle pressures of 110 ... to 160 bar. These higher pressures will be used in conjunction with slow speed engines when it is a matter of particularly efficiency.

This calculation now shows that the running gear of the double-acting Stirling engines has the same overall dimensions as the Diesel gear.

It now remains only for the cylinder head to be added to the running gear of the Diesel engine, andthe combustion system must be mounted on the Stirling running gear, Fig. 3. The combustion system of the Stirling engine is, as shown by the proprtions given in Fig. 1, approximately twice as large as the cylinder head of Diesel engines.

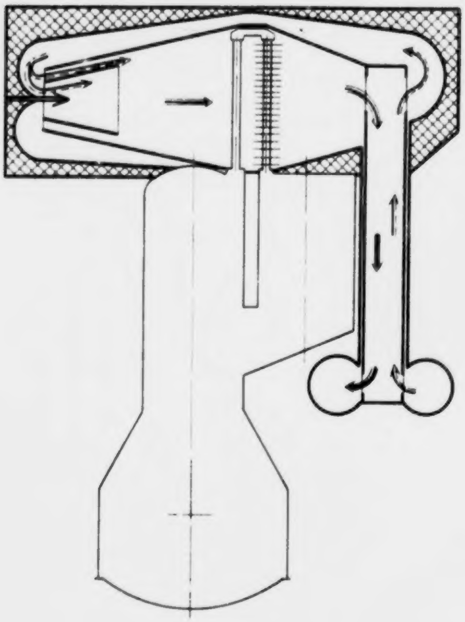


Fig. 3. SCHEME OF COMBUSTION SYSTEM

The Stirling engine allows a certain amount of leeway for arranging the elements of the combustion system, such as combustion chamber and air preheater, so that the somewhat greater volume of its combustion system can be accommodated in such a way that the actual space required by the Stirling engine is no greater than that required by the Diesel. No problems which might be inherent in the design of the Stirling engine should be therefore be anticipated when it is installed in vehicles.

In vehicular application the space needed by the cooling system becomes particular importance. The quantity of heat to be dissipated in the cooler of the Stirling engine is approximately twice as great as that dissipated in the Diesel. This calls for twice the cooling surface area or a twofold increase in the specific heat transfer rate in the cooler.

As the efficiency of the Stirling engine is directly affected by the cooling water temperature, efforts are being made to reduce the latter. However, for each application under consideration the effort expended on the cooler must be matched by an optimum gain in efficiency.

By way of example let a cooling water temperature of 60 °C be assumed. With this a useful efficiency rate of barely less than 30 % can be achieved, which is still quite good. The effective temperature difference at the cooler would then be approximately half as great as at that in vehicular Diesel engines. This means that a cooler must be used with its heat transfer surface area increased approximately fourfold or with a heat transfer rate approximately four times as great with the same surface area. New cooler construction technologies make it reasonable to assume that these increased cooling capacities can be attained by new coolers with about the same front contour.

The size comparison depicted here in the light of the most recent data shows in summary form that the Stirling engine can be accommodated in a space which must be provided for a Diesel as well. The Stirling engine, however, makes greater demands on the water-air cooler.

2. Weight

Weight is a further criterion. For the lack of precise data more detailed statements cannot be made on this point. It should merely be pointed out that the ratio of weight to volume in Stirling engines is similar to that in Diesels, i.e. it can be assumed that Stirling engines are comparable with vehicular Diesels in terms of weight as well.

3. Cost

An answer to the question of cost is being awaited from the

Stirling engine with particular urgency.

Even if no prices can be quoted here, technical and design measures taken on Stirling engines by M.A.N.-M W M enabling costs to be cut drastically should be explained here.

First, a crank mechanism has been chosen for the running gear. Experience gained by M.A.N.-M W M has shown that this combines the lowest costs with the maximum reliability and is no larger than other forms of running gear provided for Stirling engines.

A further principal characteristic of this engine type is the design of the components of the Stirling cycle space, Fig. 4. Aluminium is used in the colder parts, heat-resistant material in the warm ones. In the vicinity of the heater (heater tubes) super-heat-resistant material must be used. As it is difficult and expensive inter alia to machine these materials, the best results have been obtained with precision casting. This has the advantage that the inner and outer heat transfer surfaces have an optimum shape and can be produced in a single operation. A vacuum brazing process then enables a joint to be made without further machining.

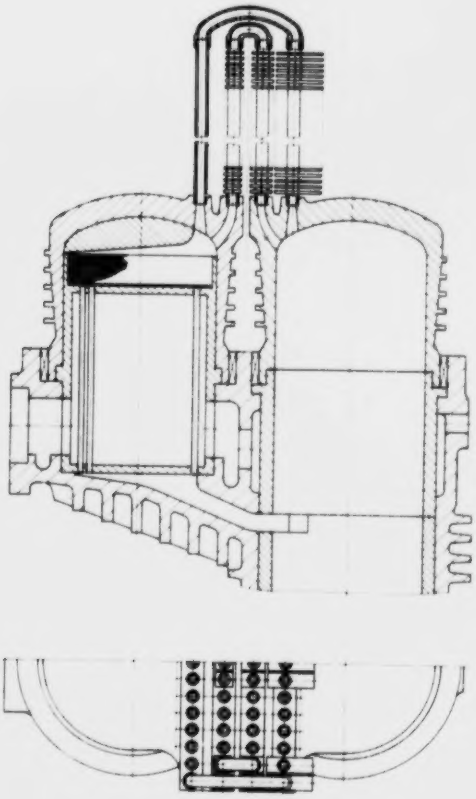
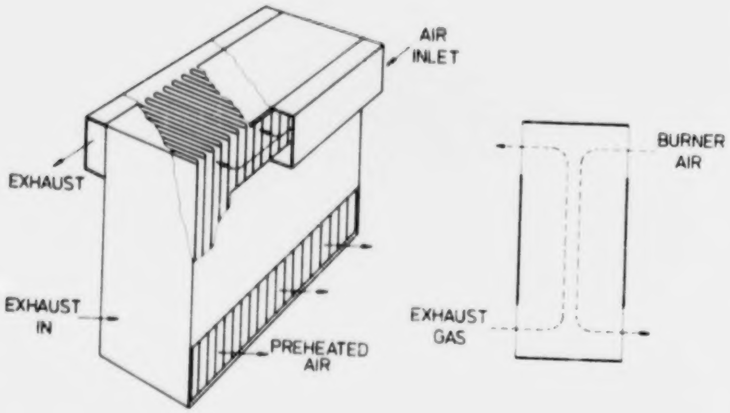


Fig. 4. STIRLING CYCLE SPACE

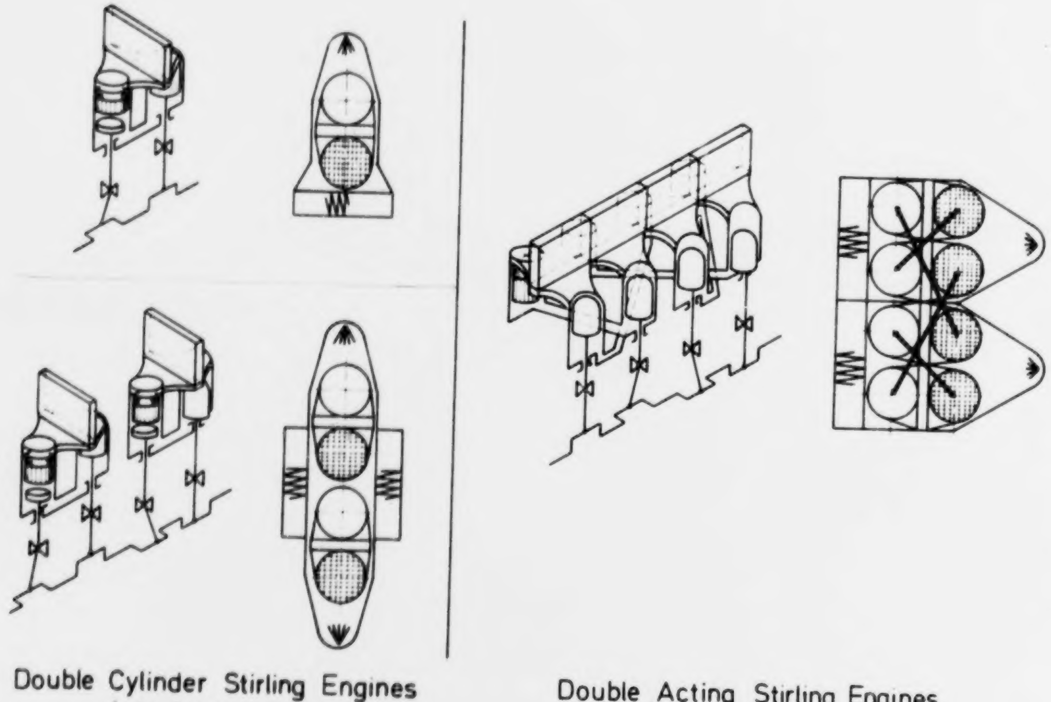
A major share of costs is made up for by the external combustion system, of which the air-preheater is the most expensive component, Fig. 5.



For the air-preheater M.A.N.-MWM have managed to select a shape which is very suitable for series production This is a plate-type counter-flow heat exchanger, the recuperator plates of which are formed by folding a sheet-metal strip.

Fig. 5. COUNTER-FLOW AIR-PREHEATER
(Folded sheet metal strip)

Even if the end seal of the package of folds is not quite clear in its technology, this form of heat exchanger still represents a design which is capable of series production.



Double Cylinder Stirling Engines
(single acting)

Double Acting Stirling Engines

Fig. 6. SERIES OF CONSTRUCTION
with great number of identical components

Stirling engines can be developed on a series basis with the elements described above. If identical running gear components (connecting rod, crossheads, piston rods, pistons, seals) are consistently used as well as the same heater heads with heater, regenerator and cooler, the smallest unit of what is called a "double-cylinder Stirling" can be constructed, Fig. 6. The small number of moving parts enables a Stirling cycle to be realized. This engine concept has the capability of favourable small dead volumes, of optimal choice of phase difference and simple arrangement of piston rod seals.

There are drawbacks, however. One of these is the fact that the running gear of this "double-cylinder Stirling" develops only half the power output of the double-acting Stirling running gear; another is that a certain amount of power gained at the hot piston has to be transfered to the cold piston via the crank gears with friction losses. However, for smaller unit outputs this design can be regarded as robust and easy-to-service.

Starting with one-cycle units greater output can be achieved by combining these units. Output can be increased further by arranging the same components to form double-acting Stirling engines with four or six cylinders in-line, or from these the V-engines.

Use of identical parts for the heater head with heater, regenerator, cooler and running gear components renders a series of Stirling engines with the power ratios 1 : 2 : 4 : 6 economically viable.

Combustion system layouts with combustion chambers and air-preheaters are also depicted in Fig. 6. These, too, are integral parts of the modular system.

4. Control

One problem that has not yet been completely solved is that of controlling the power output of the Stirling engine. Present forms of control, such as pressure-level-control and control by variable dead spaces display, for certain applications, such disadvantages as slow response or additional constructional expense. M W M has proposed a solution termed "intermittent short circuit control", Fig. 7.

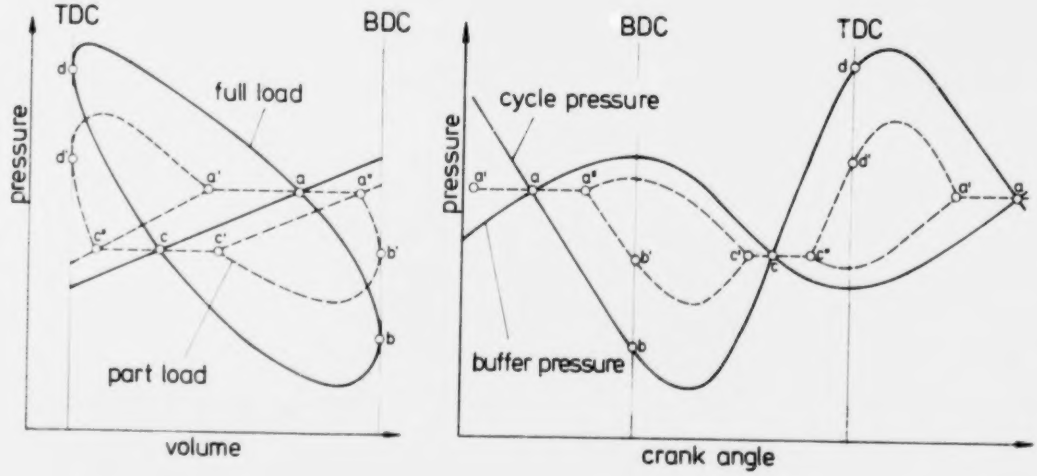


Fig. 7. INTERMITTENT SHORT CIRCUIT CONTROL (Cycle pressure)

This works on the principle of thermodynamic exclusion of sections of the piston stroke from the cycle. The internal process thus works at constant full specific inner output, but with a continuously variable swept volume.
Controlled release of the working medium into the buffer space and back causes part of the swept volume to be shut off from the Stirling cycle /3/. The interplay of cycle and buffer pressure curves causes a varying amount of work to be done in the working space according to the timings a'-a" and c'-c" set. The timings and overflow areas through which the working gas is released under control are controlled by valves.
Very quick engine response, good efficiency under partial load and moderate construction costs are expected from this form of control.

The developments and research results outlined here should contribute to the breakthrough of the Stirling engine, for this is the most significant new heat engine to meet the future demands imposed by our growing concern for the environment and by the scarcity of primary fuels.

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Symbols

C ... Constant
D ... Piston diameter
H ... Height
L ... Length
P ... Power output
R ... Crank radius
W ... Width
Z ... Number of cylinders
n ... Speed
p ... Brake mean effective pressure BMEP

Indices

D ... Diesel
S ... Stirling
m ... Mean value

2.26

STATUS REVIEW OF HYBRID HEAT ENGINE/BATTERY AND HEAT ENGINE/FLYWHEEL VEHICLES

D. E. LAPEDES and J. MELTZER
THE AEROSPACE CORPORATION
2350 EAST EL SEGUNDO BLVD.
EL SEGUNDO, CALIFORNIA, U.S.A.

A status review of work in the U.S.A. on hybrid power systems for personal passenger cars is presented. Analytical and test results for systems, subsystems, and components that evolved from EPA-funded programs are discussed within the context of the design goals established for its Alternative Automotive Power Systems Program. Advancements in the state of the art for the energy storage systems (battery or flywheel) are discussed, along with performance deficiencies that remain to be overcome. Major emphasis is placed on summarizing fuel economy and exhaust emission data.

Because of the growing concern over air pollution, interest in electric vehicles was renewed in the late 1960's and early 1970's, principally for delivery vans and trucks in Great Britain and for compact and subcompact cars in Japan. But the operating range of such vehicles remains limited -- about 50 miles with lead-acid batteries (the only economically viable electric energy storage device available today). Thus, until low-cost, high-capacity batteries are available that permit operating ranges for electric cars to be nearly comparable to those for gasoline engine-powered cars, other low-pollution vehicle concepts must be examined. One such concept that has received the attention of automobile designers in the last five years is the hybrid vehicle --a vehicle combining various power delivery systems in the powertrain to use each form of power most effectively. The most common form of system operation studied relies on a small, nearly constant power heat engine to supply energy just for vehicle cruise and for recharging a battery or flywheel. The additional power needed for vehicle acceleration is supplied by the battery, in the case of an electric energy storage hybrid, and by the flywheel, in the case of an inertial energy storage hybrid.* With this form of heat engine operation, the hybrid vehicle concept offers the possibility of reduced mobile exhaust emissions. (A shift of exhaust emissions and energy source to stationary electric generating plants, as in the case of electric vehicles, would be possible only if the energy for recharging the battery or flywheel was available from an external stationary power source, and the heat engine was then used only for supplying emergency power or for extending vehicle range on an infrequent basis.)

To evaluate various hybrid concepts, the U.S. Environmental Protection Agency (EPA) under the AAPS** Program assumed the task of planning a hybrid vehicle prototype development program. A three-year program was implemented in 1970 with the participation of several companies offering the required technical expertise. Emphasis was placed on achieving the original 1976 U.S. Federal emission standards without the use of heat engine add-on emission control devices (e.g., catalytic converters). The hybrid vehicle development program was terminated, in part because of funding limitations imposed in Fiscal Year 1971, but principally because it was found that a hybrid system with a spark ignition type of heat engine still required exhaust aftertreatment similar to that needed on conventional systems.

It should be noted that many of the study guidelines that resulted in specific powertrain design constraints for these programs have since been undergoing revision. Revised guidelines for such parameters as vehicle range, acceleration performance, cruise speed, exhaust emissions, and fuel economy could result in modification to system designs as well as to study conclusions.

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* Other types of hybrid vehicles have been proposed, but this paper discusses only electric and inertial systems.

** Alternative Automotive Power Systems

General Concept Designs and System Operation

Hybrid vehicle powertrain concepts can be grouped into two broad classes (Figure 1). The first class, the series configuration is characterized by the principle that all the energy flowing from the heat engine to the vehicle's rear wheels first passes through an intermediate energy conversion device or devices.* The second class, the parallel configuration, is characterized by the principle that some of the energy flowing from the heat engine passes directly to the rear wheels, with the balance routed in a parallel path through an energy conversion device or devices.*

Hybrid Heat Engine/Battery Vehicle

System Designs

Two major hybrid heat engine/battery system concepts funded under the EPA AAPS Program were the TRW Systems, Inc., electromechanical transmission system and the Minicar, Inc., heat engine/battery vehicle. Under a different EPA program, the Federal Clean Car Incentive Program, Petro-Electric Motors installed a heat engine/battery powertrain in a 1972 Buick Skylark. Another AAPS-funded study was performed by The Aerospace Corporation to provide an analytical evaluation of hybrid heat engine/battery vehicles. In an independent effort, General Motors built its own prototype system called Stir-Lec (modified Opel-Kadett). In this system, a readily available eight-horsepower Stirling engine is used to drive a three-phase alternating current motor through a modulating inverter. Figure 2 shows the location of the major components in the Stir-Lec I vehicle.

System Design Requirements and Achievements

TRW performed computer simulation studies to evaluate the automotive propulsion systems on the basis of total weight, volume, and efficiency over the U.S. Federal Emissions Test Driving Cycle. To confirm the study results, it built a dynamometer demonstration breadboard as "proof-of-principle" hardware. Poor correlation was found between computer-predicted results and breadboard testing results. A reduction in overall powertrain efficiency (road demand/engine output) from the predicted 76.7 percent to a nominal test value of 50 percent was the most encompassing departure. The test program allowed the major contributors to system losses to be identified. TRW stated, "In most cases, the losses can be reduced significantly by design refinement."

* Generator, motor, and battery in the electric system, or flywheel and transmission in the inertial system.

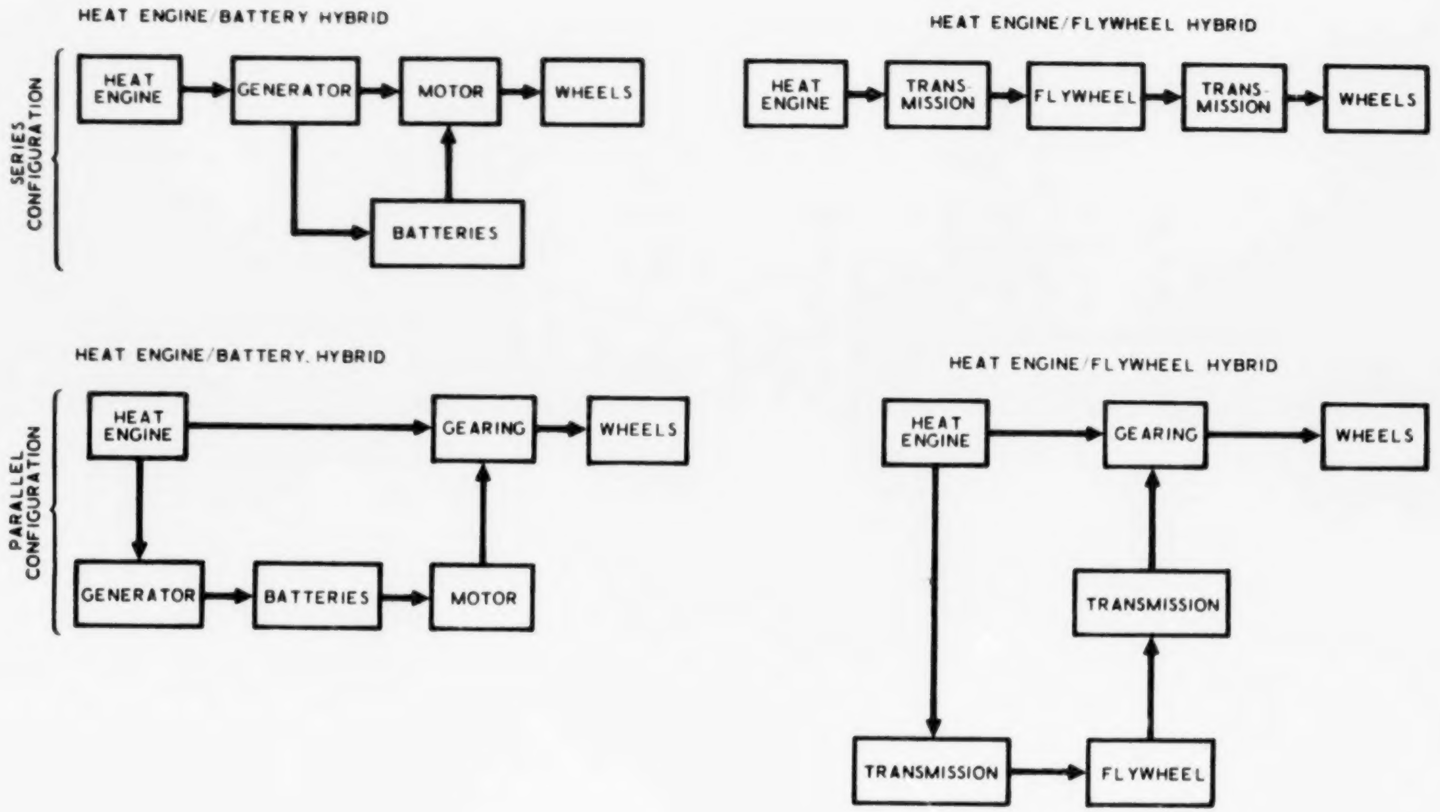

Figure 1. Simplified Schematics, Heat Engine Hybrid Vehicle Powertrain Concepts

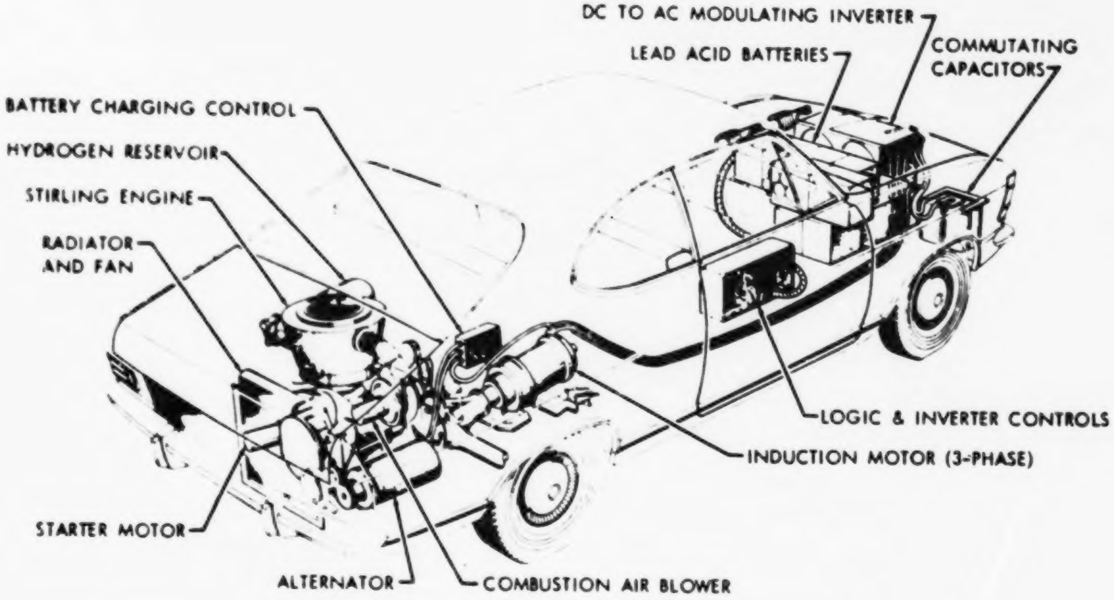

Figure 2. Phantom View of General Motors Stir-Lec I

A Chevrolet Vega engine modified for intake manifold fuel injection was used as the heat engine in the TRW powertrain system. The emission control system combined the use of a hydrocarbon accumulator with a three-component catalyst. This system proved very effective in terms of hydrocarbon (HC) and oxides of nitrogen (NO_x) control; HC emissions ranged from 34 to 73 percent of the original 1976 U. S. Federal emission standards and those for NO_x ranged from 15 to 80 percent of the standard. However, the carbon monoxide (CO) standard was exceeded during all tests except one where it was met with a seven percent margin.

The first configuration tested by Minicar did not provide sufficient electric power to reduce emissions significantly. Emissions from a final improved prototype configuration, the Hybrid C-1, were not reduced to acceptable levels and operating performance did not match that of many equivalent-size standard vehicles.

The Petro-Electric hybrid automobile was delivered to EPA in February 1974 and since has been undergoing test and evaluation.

The Aerospace Corporation study was aimed at determining the feasibility of using a hybrid heat engine/electric propulsion system to reduce exhaust emissions from passenger vehicles. Analytical results from computer calculations were as follows:

a. Only the spark ignition and gas turbine engines offer reasonable weight margins for the battery system. For the spark ignition engine, the batteries are required to deliver a specific power density of just over 200 watts per pound and a specific energy density of just over 20 watt-hours per pound.

b. Fuel economy for the family car series configuration is estimated as equivalent to that for a conventional, similar-size 1970 car.

c. For a parallel configuration with spark ignition or gas turbine engines, a reduction in most emissions to levels below the original 1975-76 Federal emission standards is predicted. The one exception is NO_x emissions from the spark ignition engine, which utilizes lean operation, an oxidation catalyst, and exhaust gas recirculation.

d. Estimated hybrid system costs for the family car indicate there will be a significant increase in vehicle purchase cost to the consumer.

At about 30 miles per hour on a level road, the General Motors Stir-Lec I vehicle achieved a fuel economy of 30 to 40 miles per gallon. Battery capabilities limited the operating range to about 30 to 40 miles at 55 miles per hour. Acceleration from 0 to 30 miles per hour took about ten seconds. It achieved a top speed of 30 miles per hour with engine power only and a top speed of 55 miles per hour with battery power added. General Motors noted that HC and CO emissions were low, but NO_x emissions were much higher than expected for the Stirling engine; the original 1976 U. S. Federal emission standards were exceeded for all three species. The expectations were that engine modifications could provide major reductions in NO_x levels.

Batteries for Hybrid Vehicles

As part of the EPA AAPS program, two investigations were initiated to study the application of lead-acid batteries to hybrid vehicles under the unique operating conditions that are imposed. Contracts were awarded to Tyco Laboratories, Inc., and to TRW (with Gould as subcontractor[*]).

In the initial effort, each contractor studied the applicability of commercial SLI (starting-lighting-ignition) lead-acid batteries to the hybrid vehicle under simulated operating conditions. Both concluded that these batteries were unsuitable because of their short life, but that lifetimes might be satisfactory with certain design modifications. Tyco redesigned its lead-acid research battery to use a quasi-bipolar arrangement. Under the same test conditions as the SLI battery, which achieved 350 cycles, the research battery lasted for 1000 cycles.

Similarly, TRW/Gould made selective changes to the SLI cell design, and their research battery achieved increased specific power density (watts per pound) by using a greater number of thinner plates per unit volume and by using lead alloy grids and conductors of higher conductivity. Tests of the new design demonstrated cell lifetimes of from 8,000 to 12,000 charge-and-discharge pulses (consisting of 30 low-rate shallow pulses for each high-rate pulse) as compared to the SLI battery which lasted for 6859 pulses.

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[*] Gould supplied the batteries tested by TRW.

In a study supported by EPA under an interagency agreement, the U.S. Army Electronics Command tested nickel-zinc battery cells for the hybrid vehicle application. These tests demonstrated that the battery could be designed to provide adequate specific energy density (watt-hours per pound) and specific power density (watts per pound), but that much more development would be needed to obtain satisfactory life.

Hybrid Heat Engine/Flywheel Vehicle

System Designs

Lockheed investigated inertial energy storage under two separate contracts. The first, Flywheel Feasibility Study and Demonstration had as its objectives the analytical determination of the feasibility of the hybrid heat engine/flywheel concept as a low-emission propulsion system for various types of passenger vehicles and the demonstration and performance evaluation of full-scale flywheels for hybrid applications. The second, Flywheel Drive Systems Study, as applied to the family car, was directed toward advancing the development of flywheel systems technology.

In the Lockheed hybrid vehicle concept, the drivetrain consists of a heat engine coupled to the flywheel and the vehicle's wheels through a planetary/hydrostatic power-splitting transmission. The heat engine compensates for drivetrain losses, and provides cruise power, accessory power, and flywheel recharging power; the flywheel provides the power required for vehicle acceleration.

Lockheed selected a disc-shaped flywheel configuration for the family car. It had an 18.6-inch-diameter conical section with a constant radius flare at the periphery and it was designed to operate in a partial vacuum within a burst-containment structure.

Concurrent with the Lockheed work, Johns Hopkins University (Applied Physics Laboratory) conducted an experimental and analytical study of high specific energy density flywheel systems for use in automotive propulsion systems. This study had two objectives: (a) the proof-of-principle demonstration of the use of filamentary or composite materials of high uniaxial tensile strength in rotor configurations, and (b) the theoretical evaluation of the performance of such flywheels alone and in combination with heat engines. Figure 3 illustrates the general arrangement of components in the Johns Hopkins hybrid heat engine/flywheel concept.

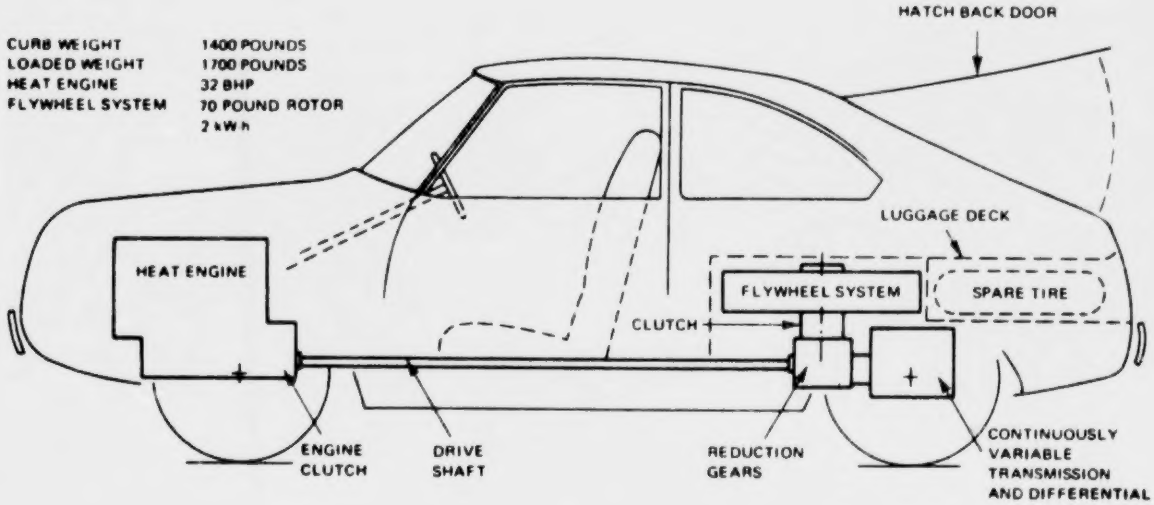

Figure 3. Johns Hopkins Hybrid Heat Engine/Flywheel Commuter Car Concept

System Design Requirements and Achievements

The main Lockheed conclusions on the hybrid heat engine/flywheel vehicle were as follows:

a. A comparative analysis of heat engine emissions for a hybrid flywheel drive contrasted with a conventional three-speed automatic transmission shows that without a catalyst, the flywheel drive offers HC, CO and NO_x emission reductions. With a catalyst, HC and CO emissions are generally equivalent between hybrid and conventional drives; the flywheel drive offers a significant reduction only for NO_x emissions.

b. Fuel economy for the flywheel drive over the U. S. Federal Emissions Test Driving Cycle is predicted to be roughly equivalent to that of a conventional transmission.

c. The estimated cost of ownership, size, and weight of a family car hybrid vehicle with a flywheel drive falls within established EPA goals.

The primary Johns Hopkins conclusions were as follows:

a. The hybrid heat engine/flywheel propulsion systems satisfy the vehicle performance requirements.

b. The spark ignition engine is the near-term choice for the heat engine.

c. The gas turbine engine seems to offer the greatest promise for the future because of its low specific weight, its potential for minimizing emissions and its operating speed, which is close to that of the flywheel.

Flywheel Design Requirements and Achievements

In parallel with the overall vehicle applicability and configuration tradeoff studies, Lockheed conducted preliminary flywheel design studies prior to fabricating and testing candidate flywheels. Six basic flywheel geometries were investigated: a pierced uniform disc, an unpierced uniform disc, a constant-stress disc, a truncated conical disc, a rim type, and a bar-type. Only materials that could be obtained in mill-run quantities were considered. The most cost effective were found to be E-glass and S-glass filamentary composites and 4340 steel. The glass composites, however, seemed readily applicable only to the bar-type flywheel geometry. The 4340 steel was felt to be an excellent candidate for low-cost flywheels in a disc configuration.

In tests to failure, the steel disc-shaped flywheel was accelerated until disintegration occurred at 35,590 revolutions per minute. This resulted in a specific energy density of about 26 watt-hours per pound and a total stored energy of one and one-tenth kilowatt-hours, which exceeded the design specification by a factor of about two, and accordingly provided a margin of safety. The glass composite bar-type flywheel disintegrated before reaching the design speed of 20,000 revolutions per minute. At failure, the maximum energy storage capacity was about half the design point value.

Lockheed's conclusions on the steel flywheel were as follows:

a. The estimated production cost of complete family car flywheel assemblies is $100, plus or minus $15, depending on flywheel configuration.

b. All the elements of a practical family car flywheel assembly are available without further technology development.

c. Early estimates of flywheel system losses as provided to the transmission contractors were highly conservative as proved by hardware testing. Flywheel windage, bearing, seal, and vacuum pump losses were substantially lower than earlier predictions.

d. Total containment of a flywheel burst at energy levels representative of what might be the case for a full-size vehicle was not successfully demonstrable with lightweight, low-cost materials.

Experimental work by Johns Hopkins was directed toward a demonstration of the "superflywheel" concept in which very high specific energy densities could be achieved. Spin tests of small-diameter filamentary composite rods and filamentary single strands were conducted in which the candidate materials exceeded the specific energy density goal of 30 watt-hours per pound. Follow-on tests of 30-inch-long, one-pound rods and bars achieved 82 to 94 percent of the desired goal.

Johns Hopkins reached the following conclusions on the testing of filamentary and composite rods and bars:

a. Spin tests demonstrate the ability to achieve 48 watt-hours per pound (without failure) with boron single-strand filaments; at burst, 36 watt-hours per pound was achieved with small graphite/epoxy composite rods, and 31 watt- hours per pound was achieved with small R-glass/polyester composite rods.

b. The larger one-pound composite bars do not meet the desired 30 watt-hours per pound goal. The best sample S-glass/epoxy achieved 28 watt-hours per pound, while the graphite/epoxy achieved 26 watt-hours per pound.

c. Tensile tests indicate that the graphite/epoxy material is substandard. While the S-glass/epoxy bars achieved satisfactory stress levels in tensile tests, numerous surface defects may have contributed to the inability of this material to meet the 30 watt-hours per pound requirement. With improved processing techniques, Johns Hopkins was confident that specific energy densities in excess of 30 watt-hours per pound could be achieved.

Transmission Design Requirements and Achievements

Under AAPS Program sponsorship, studies were conducted by Sundstrand Aviation and Mechanical Technology, Inc., on transmission designs for a parallel configuration flywheel hybrid system. Both studies examined the development of total energy transfer systems from the engine to the drive wheels, and the management of the energy storage system.

At the conclusion of its study, Sundstrand stated that:

a. A combination of mechanical, hydromechanical, and hydrostatic transmissions is a practical means of providing power for the flywheel, heat engine, and drive wheel links.

b. The selected transmission provides an infinitely variable ratio between the flywheel and the vehicle's wheels, and a nonlinear ratio (fixed by vehicle speed) between the heat engine and flywheel.

c. The specified spark ignition heat engine with the selected transmission has a greater computed fuel consumption over the U.S. Federal Emissions Test Driving Cycle than that of a typical three-speed automatic transmission. Cruise fuel consumption is greater than for the three-speed automatic below 50 miles per hour and less above this speed.

d. The theoretical fuel economy benefits that can be gained from the flywheel energy storage concept over a driving cycle, such as the U.S. Federal Emissions Test Driving Cycle, are minimal because of the small amount of energy available for storage and reuse. The more demanding the acceleration/braking duty cycle relative to maximum vehicle capability, and the heavier the vehicle, the greater are the benefits derived from the flywheel energy storage concept.

The study performed by Mechanical Technology arrived basically at the same conclusions as the Sundstrand study.

Assessment of Hybrid Vehicle Powertrain Application to Automobiles

At the time of program suspension, EPA funds expended on the hybrid vehicle development program had resulted in some major technology advancements, a much clearer definition of critical problem areas, and the establishment of preferable system operating modes. These results are indicative of information acquired in the very early phases of development, namely, proof of principle. Some forms of hybrid vehicle systems could represent an intermediate step between current automobile powerplants and a future system that relies totally on an energy storage device for delivering power to the drive wheels.

By restricting the operation of the heat engine, early studies anticipated significant reductions in exhaust emissions without the need for complex, costly exhaust treatment devices, but results to date have not verified this expected performance. While the hybrid vehicle has proven to be technically feasible, it is a complex costly system when configured to match the performance of conventional internal combustion engine-powered vehicles.

Hybridantrieb mit kinetischem Energiespeicher als Fahrzeugantrieb*

H. Schreck; F. Torres
Institut für Kraftfahrwesen, Technische Hochschule Aachen

Konventionelle Kraftfahrzeuge fahren im Stadtverkehr mit sehr hohen Kraftstoffverbräuchen. Die Ursache hierfür liegt im Fehlen einer Energie-Rückgewinnung beim Bremsen und in unwirtschaftlichen Teillastverbräuchen des Verbrennungsmotors. Durch Einsatz eines Hybridantriebes mit einer Gyro-Komponente lassen sich diese Kraftstoffverbräuche erheblich verringern. Straßenversuche zeigen, daß sich im Vergleich zu Transportern mit konventionellem Otto-Motor der Kraftstoff-Verbrauch um ca. 40 - 45 % vermindert. Die Entwicklung dieses Antriebes wird seit einem Jahr vom Bundesministerium für Forschung und Technologie gefördert.

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*gefördert vom Bundesminister für Forschung und Technologie

1. Verkehrsdynamik, Möglichkeiten zur Verringerung des Energiebedarfes bei Zyklenfahrt

Die Verkehrsdynamik in Ballungsgebieten ist zur Überprüfung der Schadstoffemissionen im Rahmen der gesetzlichen Vorschriften in einheitliche und übersichtliche Zyklen wie z.B. Kalifornia-Zyklus, Europa-Zyklus gezwängt worden. Diese Beschreibung der Verkehrsdynamik genügt nicht, den Energieverbrauch von Kraftfahrzeugen im Spektrum unterschiedlicher Verkehrssituationen zu erfassen. Um dies zu erreichen sind

a) eine Reihe, unterschiedliche Verkehrssituationen beschreibende Zyklen aufzustellen

b) eine charakteristische Kenngröße zu definieren, die es ermöglicht, diese unterschiedlichen Zyklen gemeinsam zu betrachten.

Die Forderung a) wird für Pkw in einer Untersuchung von Herrn Professor May und Herrn Dr. Plassmann [1] für den Stadtbereich Köln erfüllt. Unter Beibehaltung von charakteristischen Größen unterschiedlicher Verkehrssituationen wurden diesen unterschiedliche Zyklen zugeordnet.

Die Darstellung überstreicht für Pkw gemäß Bild 1 den breiten Bereich vom flüssigen Verkehr auf Ausfallstraßen bis zu verstopften Straßen.

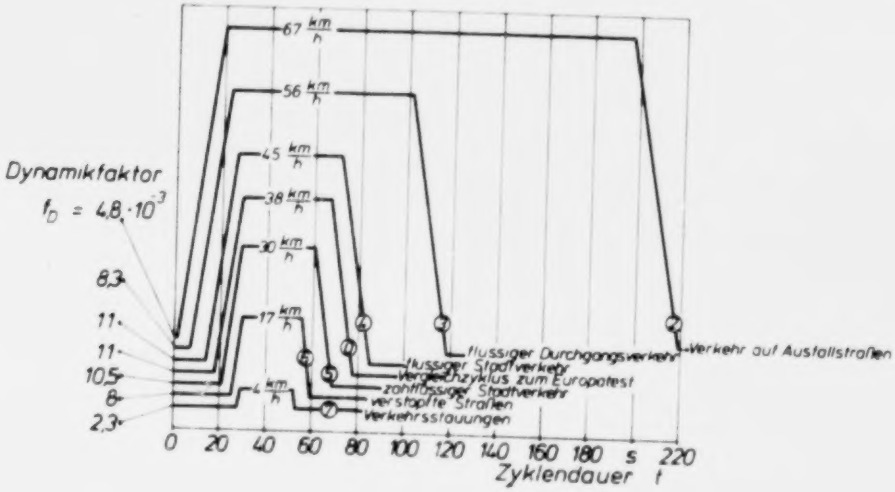


Bild 1: Darstellung von Verkehrssituationen mit unterschiedlichen Fahrzyklen und zugehörigen Dynamikfaktoren (nach [1])

Zur gemeinsamen Betrachtung derartiger Zyklen nach Forderung b) läßt sich aus der Energie-Bedarfs-Gleichung für Kraftfahrzeuge ein sog. Dynamikfaktor f_D ableiten [2]

$$f_D = \frac{1}{g \cdot n} \sum_{i=1}^{i=n} \frac{\int_0^{x'} \ddot{x}_i \, dx}{x_i} \qquad (1)$$

Seine Zuordnung zu den genannten Zyklen ist in Bild 1 dargestellt.

Die Beschreibung des bezogenen Energieverbrauches von Kraftfahrzeugen in unterschiedlichen Verkehrssituationen ist ausgehend vom Dynamikfaktor durch Hinzunahme von fahrzeugspezifischen Faktoren möglich und in der Gleichung (2) dargestellt.

$$W'_{mech} = \Big[\underbrace{f_R + f_L}_{\text{irreversibel}} + \underbrace{f_D\,(1 - \eta_R)\,(1 - \tfrac{g}{a_{(-)}}(f_R + f_L))}_{\text{reversibel}} \Big] \cdot g \qquad (2)$$

Sie beinhaltet den irreversiblen Anteil der Rad- und Luftwiderstände (f_R, f_L) und den potentiell reversiblen Anteil der vom Dynamikfaktor f_D abhängigen Beschleunigungsenergie. Der Anteil der zurückgewinnbaren Energie ist durch den Energie-Rückgewinnungsfaktor η_R gekennzeichnet.

Diese Funktion ist im rechten Teil des Diagrammes in Bild 2 in Abhängigkeit vom Dynamikfaktor f_D für einen Transporter der Masse m = 2100 kg dargestellt. Der schraffierte Bereich resultiert aus der Streubreite der Faktoren f_R und f_L.

Im linken Teil des Diagrammes sind Kurven konstanten Verbrennungsmotorenwirkungsgrades η_{VM} aufgetragen. Der Quotient aus der aufzubringenden mechanischen Energie W'_{mech} und dem Verbrennungsmotorenwirkungsgrad η_{VM} ergibt den auf der linken Abszisse des Diagrammes aufgetragenen Kraftstoff-Energiebedarf eines Fahrzeuges bei zyklischer Fahrt.

$$W'_{Krst} = \frac{W'_{mech}}{\eta_{VM}} \qquad (3)$$

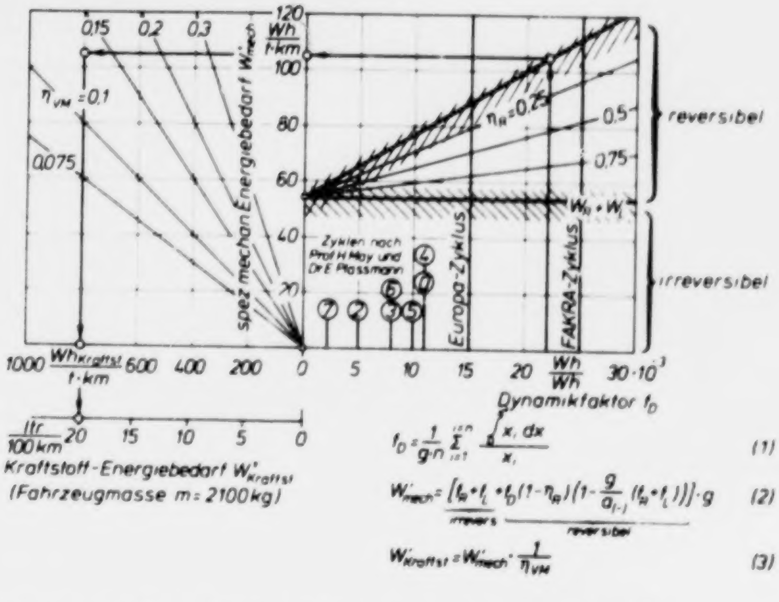


Bild 2: Diagramm zur Ermittlung des bezogenen Energieverbrauches

Ein auf Energierückgewinnung verzichtender konventioneller Transporter ($\eta_R = 0$) benötigt unter den Bedingungen eines Dynamikfaktors $f_D = 22 \cdot 10^{-3}$ gemäß der in Bild 2 mit Pfeilen versehenen Linie $W'_{mech} = 104$ Wh/t.km mechanische Energie. Durch überwiegenden Betrieb des Ottomotors im unteren Teillastbereich läßt sich aus Verbrauchskennfeldern ein mittlerer Wirkungsgrad von $\eta_{VM} = 0,13$ ermitteln. Dem Fahrzeug muß somit Kraftstoff der Energie $W'_{Krst.} = 804$ Wh/t.km entsprechend 20,0 ltr/100 km zugeführt werden. Dieser Wert deckt sich mit den im Stadtverkehr meßbaren hohen Kraftstoffverbräuchen.

Dem Bild 2 kann entnommen werden, daß sich zur Verringerung des Kraftstoff-Verbrauches bei zyklischer Fahrt zwei antriebstechnische Maßnahmen anbieten:

I. Verringerung des mechanischen Energiebedarfes durch Rückgewinnung von Bremsenergie ($\eta_R > 0$)

II. Einsatz eines Verbrennungsmotors in wirkungsgradgünstigeren Kennfeldbereichen ($\eta_{VM} > 0,1$)

Eine verkehrstechnische Maßnahme (III) bietet sich an, indem durch gleichmäßigere Gestaltung des Verkehrsablaufes der Dynamikfaktor und dadurch der mechanische Energiebedarf verringert wird. Durch die zunehmende Massierung des Verkehrs in Ballungsgebieten tritt derzeit jedoch eher ein entgegengesetzter Effekt ein. Damit verbleiben zur Verringerung des Energieverbrauches von Kraftfahrzeugen die Maßnahmen I und II. Diese lassen sich mit einer modifizierten Antriebsstruktur realisieren.

2. Struktur und Funktion eines Hybridantriebes mit Gyro-Komponente

Die Forderung I nach einem hohen Rückgewinnungs-Wirkungsgrad läßt sich realisieren, indem beim Beschleunigen und Bremsen kinetische Energie zwischen Fahrzeug und einem Gyro (Schwungrad) unmittelbar - d.h. ohne Umwandlung in andere Energieformen - ausgetauscht wird.

Ein derartiges Gyro kann dabei wegen seines günstigen Leistungsgewichtes kurzzeitig die hohen dynamischen Leistungen zum Antreiben oder Bremsen übernehmen.

Der Verbrennungsmotor braucht, verbunden mit einem Gyro, nur noch die Grundleistung aufzubringen. Er kann entsprechend klein dimensioniert und durch die Entkoppelung von Spitzenleistungsabgaben in wirtschaftlichen, engen und langsam geregelten Kennfeldbereichen betrieben werden. Mittels einer Gyro-Komponente läßt sich also auch die Forderung II nach einem hohen Motorwirkungsgrad η_{VM} realisieren.

Es gibt zahlreiche Möglichkeiten, aus den Komponenten Verbrennungsmotor und Gyro eine Antriebsstruktur zu bilden. Eine entsprechende Analyse unter Berücksichtigung zusätzlicher Randbedingungen z.B. hinsichtlich Regelbarkeit und Steigvermögen führte zu der Antriebsstruktur, die im linken Teil von Bild 3 dargestellt ist.

Sie besteht aus einem Gyro mit parallelgeschaltetem Verbrennungsmotor und einer Elektromaschine, deren Leistungen sich in einem Differentialgetriebe überlagern. Zwischen den Momenten an den Eingängen und am Ausgang des Summiergetriebes (Differential) besteht Gleichgewicht: $M_E = M_{VM} + i_G \cdot M_G = M_{Ab}$.

Das Abtriebsmoment kann also mittels des Momentes der Elektromaschine geregelt werden. Die Drehzahl am Ausgang des Summiergetriebes ist gleich der Summe der Eingangsdrehzahlen: $n_{Ab} = n_E + n_{VM}$.

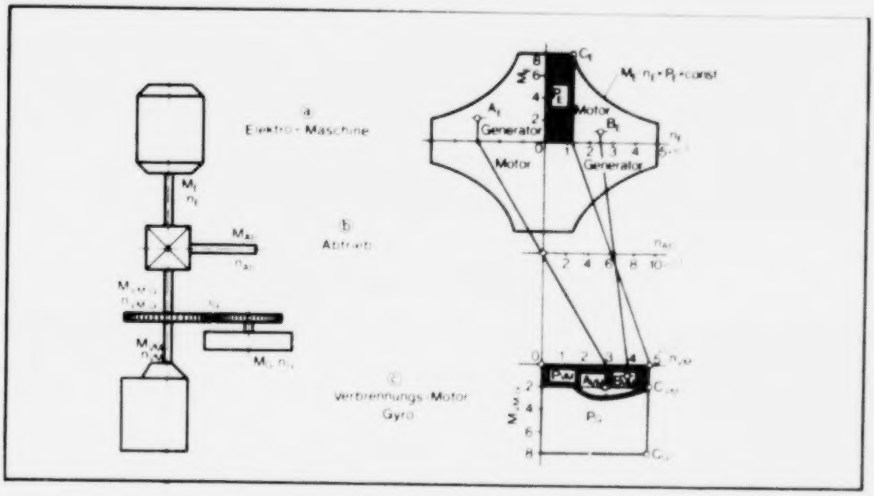


Bild 3: Struktur und Nomogramm des Hybridantriebes mit Gyrokomponente

Damit ergibt sich die Leistung als Produkt von Ausgangsdrehzahl und -Moment zu

$$P_{Ab} = M_E \ (n_E + n_{VM}).$$

Die Leistung des Antriebes kann also mittels des Momentes und der Drehzahl der Elektromaschine geregelt werden und - allerdings wegen des Gyros nur phlegmatisiert - mittels der Drehzahl des Verbrennungsmotors. Diese Beziehungen liegen dem auf der rechten Seite des Bildes 3 dargestellten Nomogramm zugrunde.

Die Kennlinie ⓐ beschreibt den Arbeitsbereich der Elektromaschine (Drehmoment über Drehzahl), die Kennlinie ⓒ den des Verbrennungsmotors mit dem parallelgeschalteten Gyro (Drehmoment über Drehzahl) und die Abszisse ⓑ die Abtriebsdrehzahl n_{Ab}, die mit dem zugehörigen Abtriebsmoment $M_{Ab} = M_E$ die am Abtrieb zu Verfügung stehende Leistung P_{Ab} ergibt.

Bei stehendem Fahrzeug und betriebsbereitem Antrieb - durch Punkte A gekennzeichnet - drehen sich die Antriebselemente ⓐund ⓒ gegenläufig. In diesem Zustand kann der Verbrennungsmotor (Betriebspunkt A_{VM}) Energie in das Gyro oder über das Ausgleichsgetriebe und die Elektromaschine in die Batterie speisen (Punkt A_E). Bei stationärer Fahrt - durch Punkte B gekennzeichnet - überlagern sich im Ausgleichsgetriebe die Leistungen der Verbrennungskraftmaschine (Punkt B_{VM}) mit der positiven oder negativen Leistung der Elektromaschine (Punkt B_E, hier im Motorbereich). Die Gyrokomponente dreht mit konstanter Drehzahl, gibt also keine Energie ab.

Im instationären Falle - durch Punkte C gekennzeichnet - erzeugt die Elektromaschine z.B.

ein hohes Moment M_E (Punkt C_E), der Verbrennungsmotor jedoch nur das Moment M_{VM} (Punkt C_{VM}). Die Differenz $M_E - M_{VM}$ wird unter Drehzahlabsenkung vom Gyro aufgebracht. Welche Anteile an der Gesamtleistung in diesem Fall die einzelnen Antriebskomponenten beisteuern, ist durch die schraffierten Flächen gekennzeichnet. Die Leistung des Gyros ist um ein mehrfaches höher als die der Elektromaschine und die des Verbrennungsmotors. Das Gyro liefert beim Beschleunigen die Leistung

$$P_G = (M_E - M_{VM}) \cdot n_G / i_G$$

3. Ausgeführtes Versuchsfahrzeug

Ein Versuchsfahrzeug mit einem derartigen Hybridantrieb wurde inzwischen ausgeführt. Der Antrieb wurde zunächst mittels Simulation am Analogrechner als Pkw- oder Transporterantrieb dimensioniert und untersucht. Die Auslegung ist an anderer Stelle [3] behandelt, so daß hier nur die wesentlichen Antriebsdaten zusammengefaßt werden:

Gyro:
$\theta_G = 0{,}612\ \mathrm{kgm}^2$
$n_{G\,max} = 1832\ \mathrm{s}^{-1}$
$m_G = 50\ \mathrm{kg}$

Verbr. Motor:
$P_{VM} = 15\ \mathrm{kW}$
$n_{VM\,max} = 523\ \mathrm{s}^{-1}$
$m_{VM} = 28\ \mathrm{kg}$

Elektromaschine:
$P_{E\,Dauer} = 11\ \mathrm{kW}$
$n_{E\,max} = 701\ \mathrm{s}^{-1}$
$m_E = 65\ \mathrm{kg}$

Batterie:
$m_B = 150\ \mathrm{kg}$
$W_{B1h} = 4{,}1\ \mathrm{kWh}$

Bild 4 zeigt einen inzwischen ausgeführten Antrieb. Auf der linken Seite des Differentialgetriebes ist die Elektromaschine, auf der rechten der Verbrennungsmotor angeflanscht. Das Gyro ist oberhalb des Differentialgetriebes angeordnet und dreht um eine vertikale Achse.

Bei einer installierten Leistung von $P_E + P_{VM} = 26$ kW gibt der Antrieb in dynamischem Falle bis zu 100 kW ab.

Dieser Antrieb ist einschließlich der zugehörigen Nebenaggregate wie Regelung und Batterie in einen Transporter Bild 5 eingebaut worden.

Die Funktionserprobung dieses Fahrzeuges ist auf dem Rollenprüfstand des Institutes, der jedoch nur stationäre Betriebszustände erlaubt, durchgeführt worden. Die dynamische Funktionserprobung sowie die Ermittlung des Kraftstoff-Verbrauches unter zyklischen Fahrbedingungen sind auf einer ebenen Versuchsstrecke, die aufgrund ihrer Länge jedoch nur Dynamikfaktoren über $f_D = 12 \cdot 10^{-3}$ zuläßt, gefahren worden.

Die Auswahl der Versuchszyklen entspricht der Verteilung der Dynamikfaktoren in auftretenden Verkehrsabläufen. Die Meßwerte Weg und Geschwindigkeit sind über der Zeit mit einer Schlepprad-Meßeinrichtung (Peiseler-Labor-Kombination) aufgetragen worden.

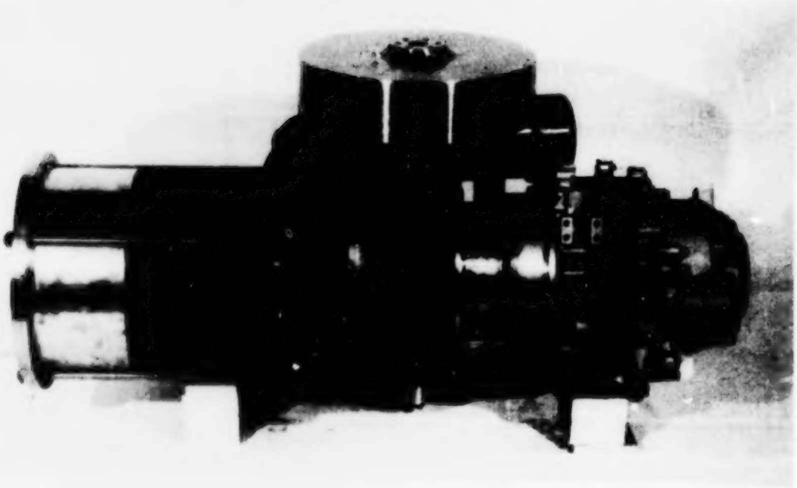


Bild 4: Hybridantrieb mit Gyrokomponente

Bild 5: Versuchsfahrzeug mit Hybridantrieb

Bild 6 zeigt den Geschwindigkeitsverlauf und zugehörige Weg-Marken mit dem Hybrid- bzw. dem Vergleichsfahrzeug zurückgelegten Zyklus der Dynamik $f_D = 22 . 10^{-3}$. Hierbei beschleunigt das Hybrid-Fahrzeug im Mittel mit $a_m = 1,2 \text{ m/s}^2$ und verzögert mit $a_{(-)} = 1,4 \text{ m/s}^2$. Es erreicht eine Geschwindigkeit von 50 km/h in 10,8 s.

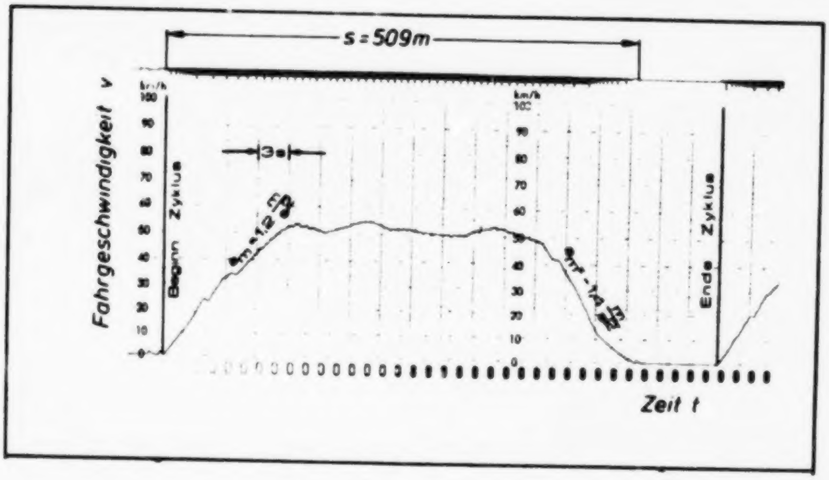


Bild 6: Fahrtverlauf eines Testzyklus mit Dynamikfaktor $f_D = 22 \cdot 10^{-3}$

Der Kraftstoff wird den Fahrzeugantrieben über Verbrauchs-Meßgläser zugeführt. Es wurde jeweils der gesamte Verbrauch an Kraftstoff nach einer Reihe von gleichartigen Zyklen unter Beachtung eines im Mittel gleichen Batterie-Ladezustandes ermittelt.

Bild 7 zeigt die auf 100 km Strecke bezogenen Kraftstoffverbräuche.

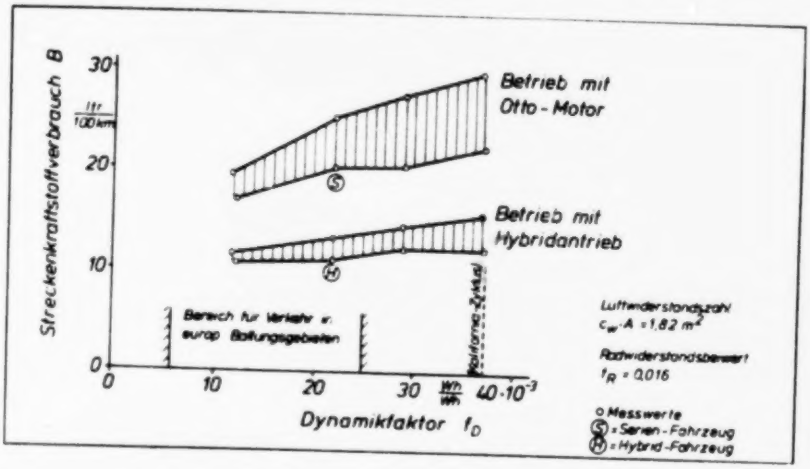
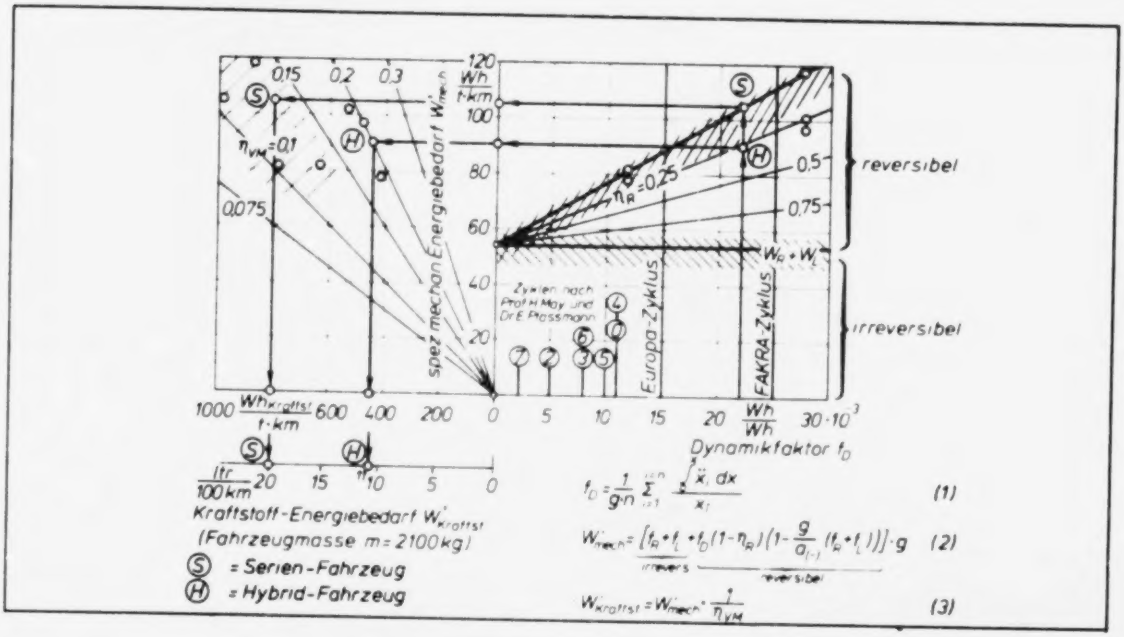


Bild 7: Streckenkraftstoffverbrauch eines Fahrzeuges der Masse m = 2100 kg mit Hybrid- bzw. Otto-Motoren-Antrieb in Abhängigkeit des Dynamikfaktors

Für das Fahrzeug mit Otto-Motor ergeben sich die oberen, für die des Hybridfahrzeuges die darunter aufgetragenen Meßwerte. Gegenüber den üblichen Kraftstoff-Verbrauchswerten des Otto-Motors zeigt der Hybridantrieb bei gleichem Fahrtverlauf einen um 40 % geringeren Strecken-Kraftstoff-Verbrauch. Mit zunehmendem Dynamikfaktor vergrößert sich diese Differenz.

Die Meßergebnisse zeigen für die Fahrzeuge bei gegebenem Dynamikfaktor einen unterschiedlich großen Streubereich. Dieser begründet sich beim Serien-Fahrzeug durch die vom Fahrer abhängige Betriebsweise des Motors und durch die Geschwindigkeits-Abhängigkeit von Fahrzeugparametern, während beim Fahrzeug mit Hybrid-Antrieb nur letzterer Einfluß maßgebend ist.

Diese einzelnen Meßpunkte sind in Bild 8 eingetragen. Sie erlauben eine Analyse nach thermodynamischem und mechanischem Energieanteil. Die beiden durch Ⓗ und Ⓢ gekennzeichneten, aus gleicher Versuchsreihe stammenden Meßwerte werden gesondert herausgegriffen:



$$f_D = \frac{1}{g \cdot n} \sum_{i=1}^{i=n} \frac{\int \ddot{x}_i \, dx}{x_i} \qquad (1)$$

$$W'_{mech} = [\underbrace{f_R + f_L}_{irrevers} + \underbrace{f_D(1-\eta_R)(1-\frac{g}{a_{(-)}}(f_R+f_L))}_{reversibel}] \cdot g \qquad (2)$$

$$W'_{Kraftst} = W'_{mech} \cdot \frac{1}{\eta_{VM}} \qquad (3)$$

Bild 8: Diagramm zur Ermittlung des bezogenen Energieverbrauches

Der Kraftstoffverbrauch des Fahrzeuges Ⓢ von 20 ltr/100 km ist in einem Zyklus der Dynamik $f_D = 22 \cdot 10^{-3}$ gemessen worden. Da sowohl irreversible als auch reversible Anteile der mechanischen Energie aufgebracht werden, benötigt das Fahrzeug $W'_{mech} = 104 \frac{Wh}{tkm}$ an mechanischer Energie. Zusammen mit dem gemessenen Kraftstoffverbrauch ergibt dies einen über den Zyklus gemittelten Verbrennungsmotoren-Wirkungsgrad $\eta_{VM} = 0,13$.

Das Fahrzeug mit Hybrid-Antrieb Ⓗ benötigt, bei gleichem Zyklus 11 ltr/100 km. Aufgrund des engen Betriebsbereiches seines Verbrennungsmotors kann mit der gemessenen Drehzahl und Drosselklappenstellung hier eindeutig ein Wirkungsgrad $\eta_{VM} = 0,2$ (Wankel-Motor) zugeordnet werden.

Zusammen mit dem Dynamikfaktor ist damit ein Energie-Rückgewinnungs-Wirkungsgrad von $\eta_R = 0,3$ zu ermitteln. Dieser Wert wird bei höherer Dynamik überschritten.

Die erreichten Versuchsergebnisse zeigen, daß der günstige Kraftstoffverbrauch des Hybrid-Fahrzeuges durch 2 Maßnahmen erreicht wird:

1. durch Rückgewinnung von Bremsenergie: 14 %

II. durch günstigere Einsatzbedingungen des Verbrennungsmotors: 31 %

Die Verbesserung insgesamt beträgt in diesem Falle somit 45 %. Damit bestätigen sich mit diesem Versuchs-Antrieb die vorangegangenen theoretischen Ermittlungen [4].

Nach der mit Prüfstandsuntersuchungen und Rechnersimulationen vorgesehenen Antriebsoptimierung kann damit gerechnet werden unter Beibehaltung hoher dynamischer Fahrleistung, über einen breiten Verkehrs-Dynamikbereich eine Kraftstoff-Verbrauchs-Verminderung von 50 % zu erreichen.

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Abkürzungen verwendeter Begriffe:

a_m	$[m/s^2]$	Mittlere Beschleunigung
$a_{(-)}$	$[m/s^2]$	Mittlere Bremsverzögerung
A	$[m^2]$	Stirnfläche Fahrzeug
B	$[dm^3/h\ ;\ dm^3/100km]$	Kraftstoffverbrauch
$c_W \cdot A$	$[m^2]$	Luftwiderstandszahl
c_W	$[-]$	Luftwiderstandsbeiwert
f_D	$[-]$	Dynamikfaktor nach Formel (1)
f_L	$[-]$	Luftwiderstandsfaktor; $f_L=(c_W \cdot A \cdot \varrho \cdot v^2)/(2 \cdot m \cdot g \cdot x)$
f_R	$[-]$	Radwiderstandsbeiwert
g	$[m/s^2]$	Erdbeschleunigung
i_G	$[-]$	Übersetzung Gyro
m	$[kg]$	Masse Fahrzeug
m_B	$[kg]$	Masse Batterie
m_E	$[kg]$	Masse Elektromaschine
m_G	$[kg]$	Masse Gyro
m_{VM}	$[kg]$	Masse Verbrennungsmotor
M_E	$[Nm]$	Drehmoment Elektromaschine
M_{VM}	$[Nm]$	Drehmoment Verbrennungsmotor
M_G	$[Nm]$	Drehmoment Gyro (Schwungrad)
M_{Ab}	$[Nm]$	Drehmoment Abtrieb Hybridantrieb
n	$[-]$	Anzahl einzelner Zyklen
n_{Ab}	$[s^{-1}]$	Drehzahl Abtrieb Hybridantrieb
n_E	$[s^{-1}]$	Drehzahl Elektromaschine
n_G	$[s^{-1}]$	Drehzahl Gyro
n_{VM}	$[s^{-1}]$	Drehzahl Verbrennungsmotor
P_{Ab}	$[kW]$	Leistung Abtrieb Hybridantrieb
P_E	$[kW]$	Leistung Elektromaschine
P_G	$[kW]$	Leistung Gyro
P_{VM}	$[kW]$	Leistung Verbrennungsmotor
t	$[s]$	Zeit
v	$[m/s\ ;\ km/h]$	Fahrgeschwindigkeit
W_{B1h}	$[Ws\ ;\ kWh]$	Batterie-Energie bei einstündiger Entladung
W_{Krst}	$[Ws\ ;\ Wh]$	Kraftstoffenergie
W'_{Krst}	$\left[Ws/kgm\ ;\ Wh/t \cdot km\ ;\ ltr/100km\right]$	Bezogener Kraftstoff-Energiebedarf
W_L	$[Ws\ ;\ Wh]$	Luftwiderstands-Energie
W'_{mech}	$\left[Ws/kgm\ ;\ Wh/t \cdot km\right]$	Mechanischer, bezogener Energiebedarf
W_R	$[Ws\ ;\ Wh]$	Radwiderstands-Energie
x	$[m]$	Weg bei Zyklenfahrt
x'	$[m]$	Beschleunigungsweg
$\ddot{x}$	$[m/s^2]$	Fahrzeugbeschleunigung
η_{ges}	$[-]$	Gesamtwirkungsgrad nach Formel (4)
η_R	$[-]$	Energie-Rückgewinnungs-Wirkungsgrad
η_{VM}	$[-]$	Wirkungsgrad Verbrennungsmotor
ϱ	$[kg/m^3]$	Luftdichte
Θ_G	$[kg\,m^2]$	Trägheitsmoment Gyro

THE INTEGRATED SYSTEM "ELECTRIC TRACTION ON THE ROAD" AND ITS DEVELOPMENT IN THE FEDERAL REPUBLIC OF GERMANY. LE SYSTEME ENTIER "TRACTION ELECTRIQUE SUR LA ROUTE" ET SON DEVELOPPEMENT DANS LA REPUBLIQUE FEDERALE ALLEMANDE .

DR.-ING. H.-G. MUELLER
GES, Gesellschaft für elektrischen Strassenverkehr mbH.
4000 - DUESSELDORF 30
Tersteegenstrasse 77

The most important problem for the future is not so much lower pollution of the environment but long terme insurance of energy resources. Therefore on-the-road traffic supplied only by petroleum must be alternated as quick and as far as possible to new propulsion energy. Electricity here has major advantages. However during the development of storage batteries and cars some principal rules of electricity supply must be respected.

Le problème le plus important pour l'avenir n'est pas du tout la diminuation de la pollution de l'environnement mais surtout la garantie d'une disponibilité à long terme de sources d'énergie. Donc le trafic routier approvisionné uniquement par pétroléum a besoin d'une autre énergie le plus tôt possible. C'est bien ici que l'électricité possède l'avantage décisif. Toutefois il faut respecter les règles principielles de l'approvisionnement d'électricité lors du développement des battéries et des véhicules.

Das wichtigste Zukunftsproblem ist nicht geringere Umweltbeeinträchtigung sondern langfristige Sicherung der Energiequellen. Deswegen muss der einseitig auf Mineralöl gestützte Strassenverkehr schnellstens und so weit wie möglich auf eine neue Antriebsenergie umgestellt werden. Elektrizität hat hier entscheidende Vorzüge. Allerdings muss man bei der Entwicklung der Speicherbatterien und der Fahrzeugen die prinzipiellen Gesetze der Elektrizitätsversorgung berücksichtigen.

INTRODUCTION

It is a common error to think that an electric car can be built by only exchanging the propulsion motor and by substituting the fuel tank by an electric battery. When discussing the new construction the result will always be that electrics will have only a limited chance as long as batteries do not become at least 10 times better. In all considerations it is supposed that principal service conditions of an automobile must remain unchanged. One must not forget that the individual automobile originated as a useful link to other traffic and transport systems and can therefore never be the only solution of all transport problems.

Since the petroleum crisis one has learned that on-the-road traffic - as one of the most important factors of national economies- depends exclusively on a secure energy supply. It was perceived too late that automobiles have no alternative to petroleum derivates as propulsion energy. It is incomprehensible that still today worldwide research is concentrated on low polluting engines accepting the fact that higher fuel consumption must be taken in account.

The interest in electric propulsion is in the first line directed to the being free of exhausted gases and the low noise level. Only very slowly public opinion understands the decisive advantage that electricity as propulsion energy for on-the-road vehicles can be generated on the basis of various primary energies. Most of them - especially nuclear and coal resources- will be long terme guaranteed.

However electricity supply has to consider some principal physical rules having important economic consequences too. A concept for electrically supplied on-the-road traffic may not surpass these facts. Development of electric propulsion systems and storage batteries must run parallel to the development of the supplying aggregates considering the technical requirements of the existing public electrical grid.

DISTRIBUTION OF TRANSPORT TASKS

We all know that intercontinental transport of goods and persons as well as long distance traffic can only function in connexion with regional traffic carriers as links.

Unfortunately public transport on overcrowded roads in the past lost more and more importance because of low reliability, delays and other poor comfort. Whenever these disadvantages can be compensated it will take a lot of time and an immense amount of money.

More and more doubts come in the discussion that public households will not be able to fulfil the increasing financial requirements.

THE IMPORTANCE OF INDIVIDUAL CARS

Individual cars of different sizes are surely the cheapest way to transport goods and persons over regional distances. Most of the streets must be built either as a part of the local infrastructure or by strategic or other safety reasons. The owner of the car buys his vehicle normally without public financial assistance and does the job of driving ,cleaning and minor maintenance unpaid. Much more he enjoys to have a car and to look after it.

Figure 1 shows the tendency of motorization increase.

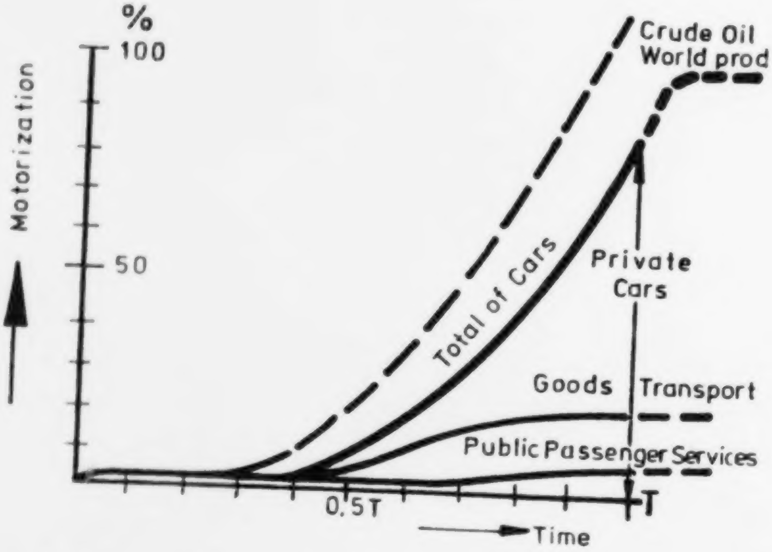

Figure 1 - Trends of Motorization.

It should be recognized that the trend seems to be worldwide the same.
Only the period of time "T" from the beginning up to a certain saturation differs considerably and depends on the sociological and economical conditions of the various countries.
No more than about 15 % of the worlds population is living in areas where the prognosticated maximum of 350-380 cars per 1000 persons is nearly reached.
Figure 1 also shows the tendency of increase of commercial vehicles either for transport of goods or persons.

It is interesting to note that industrialization normally begins with an increase of commercial vehicles but the explosion of private motorization comes much later and is a typical symbol for the style of living of a nation based on its productivity.

In so far the automobile becomes a status symbol but we must have in mind that 85 % of the driven distances we really need to feel free in the selection of housing and working areas, education and shopping centers and recreation grounds of different kinds. This high quality of life we can appreciate in a district of about 30-50 km in diameter, but only a small percentage of the worlds population enjoys this freedom and standard.

ENERGY SUPPLY FOR "ON-THE-ROAD" TRAFFIC TODAY AND IN THE FUTURE

Nearly all present cars have internal combustion engines (ICE) powered by gasoline or Diesel fuel.
Both are refined out of petroleum.

Figure 2 shows that approx. 70 % of the worlds petroleum production is consumed by nations being near to the saturation point according to fig.1.

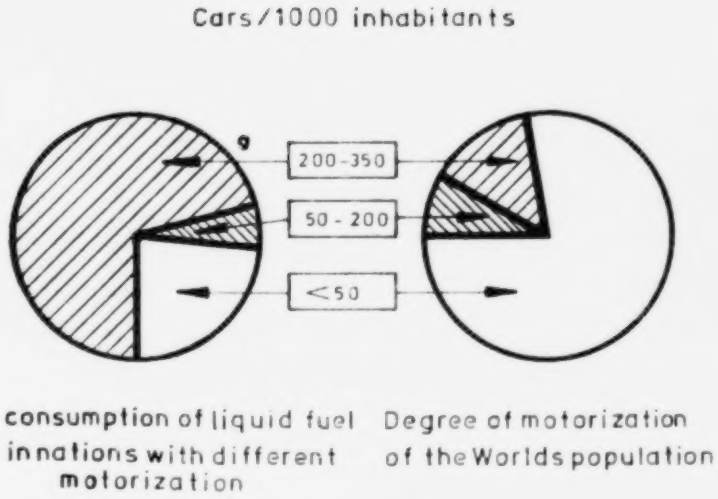

Figure 2 - Relation between oil - consumption and Motorization.

May be an approximate 10 % are being used by those within the increasing part of the curve. The last 20 % are being consumed by low motorised nations, a mere 60 % of the worlds population. It is a rather unpleasant consideration that the latest statement makes clear that during the next 3 decades a serious shortage of petroleum supply will be unavoidable.

We should consider the fact that the next generations will have to pay the bill of our wastefullness. The logical consequence can only be to change as much as possible the individual traffic to other energy supplies in due time.
We cannot wait untilnew development processes succeed in the production of low price synthetic liquid fuels.
They will in a more distant future be particularly needed for air traffic, ship transport and for substitution of petro-chemical products in many other cases. What we need today is a substitute which is already technically developed enough and available at an acceptable price.
The unique alternative is ELECTRICITY having the following advantages :

- no influence on its quality from the used primary energy
- methods of generation and distribution on a high level of availability and safety
- distribution system already installed and still expanding
- low and stable prices because of the high efficiency of the grid
- no pollution problems near the consumer and acceptable as well as decreasing pollution by generation and distribution.

The conclusion is simple. What we need are economical instead of low polluting propulsion systems. All public and industrial investment should be concentrated in the development of components for electric traffic ready for production.

MAIN TASKS FOR FUTURE RESEARCH AND DEVELOPMENT

As already mentioned the following items must be studied synchronous

- infrastructure of supply
- storage batteries
- vehicle and electric propulsion elements.

The supplying aggregates (battery chargers) will be fed out of the public medium voltage and low voltage grid. Mainly the latter should be utilized because installations are practically available in all houses. With reference to other existing consumers usually the load capacity of the connexion should be limited to approx. 5 kW.

HERE IS THE MAJOR DIFFERENCE BETWEEN GASOLINE SUPPLY AT A STATION AND ELECTRICITY SUPPLY OUT OF THE PUBLIC GRID.

It can easily be calculated that a filling hose of a petroleum station represents an electric load of approx. 30.000 kW, from which at a medium efficiency of 16 % still approx. 5000 kW filling load can be utilized in the car. On the other side the electric feeder gives a usuable feeding load of only approx.3 kW calculated with a higher efficiency of an electric car of approx. 60-70 %.

In other words conventional cars can be filled up with liquid fuel during approx. 2 hours integrated over the year but electric cars need recharging times that are some 1000-2000 times longer. This is acceptable considering that the majority of individual cars is in use only 300-500 hours a year which means they are spending more than some 8000 hours annually in parking areas. More than sufficient time is available, provided that a sufficient number of connexions to the public grid is installed and can be utilized in a convenient way by a relatively high degree of automatisation. The mechanism of this coupling system as well as the research on some electric phenomena must urgently be developed. Measuring technology is also an important part of this program because it would be the first time that electricity will be sold "over the road".

In cases of higher demand, this system can be accomplished by some connexions with higher load values to reduce the recharging time.The maximum load of course is limited. With respect to losses and heat problems of the battery the charging capacity should not be higher than the medium discharge capacity.
In other case additional conducting material and weight must be installed and carried by the car.

Electric batteries need some service every 1-3 months. It is recommended to exchange the battery therefore, which is a matter of some minutes. The user hereby keeps the vehicle in continuous service. For persons driving over longer daily distances these battery exchange stations are a very important part of the infrastructure. Exchanging of batteries is the key to continuous service around the clock.

Starting from these 3 components of the supply system the aim of development for electric storage batteries can be defined. Firstly the specific energy weight should be reduced as far as possible to diminish the total weight of the car. Higher energy capacity and higher load capacity must be developed in parallel. Only then as a next step a larger range can be envisaged.

Considering that by physical reasons an electric accumulator of acceptable weight never will have the same energy capacity as a liquid fuel tank, it is important to decide which maximum distance a car must be able to run between two longer parking stops. 50 km seem to be sufficient for local traffic and 100 km for interurban traffic in the region. If the battery is continuously recharged during the stops it is easy to get a daily range of 100-120 km out of a battery dimensioned for only 50 km. Statistics show that the majority of these single distances are about 10 km and that means that the battery will relatively seldom be completely discharged.

An important task is to develop batteries for partial discharge over longer periods without negative influence on their quality. Also the envisaged goals for the needed cycle life of batteries must be defined. With respect to technical progress during the next decade and the high mechanical stresses in a car it is not wise to build traction batteries for service times longer than those of the vehicle itself i.e. for more than 5-10 years. During that time the installed energy capacity will be used 1000 to 2000 times. The higher the energy capacity the lower is this number. Only if we take in account that traction batteries could be used later as load batteries in the grid a life time of 20 years could become interesting. Vehicles and propulsion systems have already reached the highest level of development. Further research will lead to some optimisation and then to methods making also larger electrical motors mass-producible. The same can be stated for the control equipment which must become cheaper and simpler as well. Compromises between electric and mechanical control have to be studied in this field.

Electrical elements usually have a longer life time due to their lack of mechanically stressed parts. Following this fact shortly terminated elements of the vehicle must be built either stronger or easier to exchange. Conventional cars often get a second motor, electric cars in the future will get a second body.

Heating and air-conditioning and the board supply system are today fed out of the overflow of losses of the ICEs. Also these auxiliaries have to be studied again for a more efficient use in electric cars.

STATE OF DEVELOPMENT IN THE FEDERAL REPUBLIC OF GERMANY

The most important result of our studies and experiments is the concept itself as presented above. It is based on test results collected by small fleets of vehicles built in close cooperation between manufacturers of the automotive and electrical industry. First tests were concentrated on buses and vans with different propulsion systems. After intensive experiments on test circuits the vehicles were put in practical service on the road. Automotive industry is based on mass production and the high investment for expensive assembly lines can be responsed only on the basis of statistically insured test results gathered with a larger number of test objects. Beginning with some 10 different test objects it seems to be useful to enlarge the fleets to some 100. The number of interesting technical variants as well as the different service conditions over the country is large and therefore good cooperation and coordination is needed to save money and time. For this reason G E S - working as catalyst- was founded.

FINAL CONCLUSION

Electric traction on-the-road is an important task for the future to solve energy problems for technical and economical reasons. Only electricity can help to substitute a lot of petroleum based fuel for cars during the next 3 decades. Electric cars fulfil perfectly all the requirements of protection against pollution especially in urban areas.

Research and development must be coordinated having in mind that production and distribution of electricity follow principal rules which must be considered when planning the supplying infrastructure, the energy stores, the vehicles and their propulsion system.

Some changes of the todays traffic customs have to be accepted but still the automobile will keep its immense importance as an integrated part of the transport and traffic system of all nations. This applies to the highly developed countries and mainly also to the population in the lessed developed parts of the world.

The development of a new total system needs time, technical engagement and mainly a remarkable financial amount, even if many components can be taken from highly sophisticated well known similar technical fields.

Governmental and industrial authorities as well as the population should finally recognize their great responsibility for the long terme insurance of on-the-road traffic. What we need are not so much low polluting ICEs but propulsion systems using a long terme guaranteed energy like electricity.

Till this aim is reached the device for the next years will be to save petroleum for later generations even if serious restrictions must be accepted.

IMPACTS OF ELECTRIC CAR USE IN LOS ANGELES

W. F. HAMILTON
General Research Corporation
P.O. Box 3587
Santa Barbara, California 93105

Environmental, energy, and socioeconomic impacts of electric car use in the Los Angeles region in 1980-2000 were investigated. Prospective applicability of limited-range electric cars to Los Angeles driving patterns was analyzed. Four-passenger subcompact cars were characterized for the analysis with representative future storage batteries permitting daily driving ranges adequate for either limited use as a second car, or for general urban use including freeway commuting. Air pollution and energy consumption impacts were given special attention.

The scope of this study was limited to battery-electric cars in the years 1980-2000. Study focus was on California's South Coast Air Basin, an area of some 25,000 square kilometers bounded by mountains and ocean; this area includes greater Los Angeles and had 1970 populations of 10 million people and over 5 million cars. Study emphasis was on environmental, energy, and socioeconomic impacts of electric car use rather than on vehicle technology and design.

As a starting point for impact calculation, future electric cars were briefly characterized. Four representative battery technologies were considered, with basic capabilities shown in Fig. 1. Lead-acid battery characteristics were projected from those of high-performance electric vehicle batteries which have already been tested in electric cars. Characteristics of advanced batteries were taken from achievements and goals of development programs at Gould, Inc., Energy Development Associates, Inc., and Argonne National Laboratory.

A computer program was developed to model battery discharge according to Fig. 1 while meeting power requirements of electric cars for urban driving.

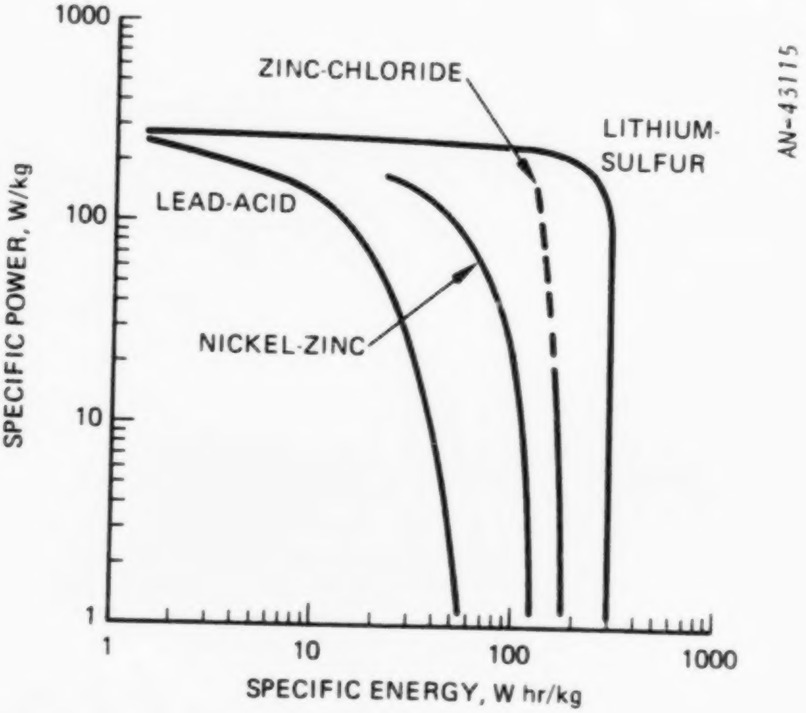

Figure 1. Assumed Battery Energy

The SAE Metropolitan Area Driving Cycle for electric cars was used in this program; it calls for a stop each 1.6 km, an average speed of 39 km/hr, and an energy requirement per km very near that of the US Federal driving cycle used in official measurement of auto exhaust emissions and fuel economy.

After a parametric analysis, the specific car ranges of Table 1 were selected for the impact analysis. The electric cars were four-passenger subcompacts with performance slightly below that of current low-performance conventional subcompacts; they were capable of accelerating from 0 to 65 km/hr in 10 sec., and of cruising on a freeway at 100 km/hr. Special tires with low rolling resistance, an aerodynamic drag coefficient of 0.4, and a dc traction motor with SCR chopper controller and two-speed automatic transmission were assumed.

TABLE 1. CHARACTERISTICS OF ELECTRIC CARS
(for urban use)

Availability, year	1978	1980	1985	1990
Battery Type	lead-acid	nickel-zinc	zinc-chloride	lithium-sulfur
Test wgt, kg	1803	1602	1338	1168
Urban Driving Range, km	87	232	233	224
Energy Requirement, kWhr/km	.49	.32	.25	.28
Cost (less battery), 1973 dollars	2977	2945	2891	2795

Characteristics of batteries used in the electric cars are shown in Table 2. Lifetimes shown assume urban driving of about 48 km/day. For the lead-acid battery, the projected range of lifetimes is based on current experience; the longer life projection is quite optimistic. For the nickel-zinc and zinc-chloride batteries, indicated lifetimes assume that developers' goals for lifetimes of 400 and 500 deep discharges, respectively, will be achieved, and that life with partial discharges will be increased in inverse proportion to discharge depth. For the lithium-sulfur battery, which must be maintained at a very high temperature, the indicated lifetime range is assumed to be independent of use.

Electric car ranges of Table 1 were selected after a new analysis of Los Angeles travel data which had been collected in an extensive 1967 survey. Figure 2 shows the resultant distribution of driving distances on the survey

TABLE 2. CHARACTERISTICS OF ELECTRIC CAR BATTERIES
(for urban car use)

Battery Type	lead-acid	nickel-zinc	zinc-chloride	lithium-sulfur
Weight, kg	681	495	259	136
Energy Density, kWhr/kg	27.8	96	157	276
Energy Efficiency, %	46	66	70	62
Life, years	1.3-3.4	5.8	7.3	3-5
Cost, 1973 dollars	1200	4400	600	600

day for drivers with cars exclusively available to them. Most present Los Angeles drivers and vitually all future Los Angeles drivers fall in this category. The distribution of Fig. 2 was derived from about 120,000 separate trips made by 30,000 drivers at 20,000 representative households. It shows that cars of Table 2 with 230-km range would be inadequate on only 2% of urban driving days. The car with 87-km range, however, would be inadequate on about 1 driving day out of 6, a frequency considered unacceptable. As a secondary car in a two-car household, however, where longer trips were accomplished by the primary car, even this car could be adequate on over 97% of driving days. Average daily car travel in Los Angeles has been growing quite slowly since the 1930's, and little future change is expected. The average in Fig. 2, 46 km, is projected to increase only 6% by the year 2000.

Simple overnight recharging, rather than a system of battery exchange and recharge stations, was assumed. Overnight recharging would be easiest arranged

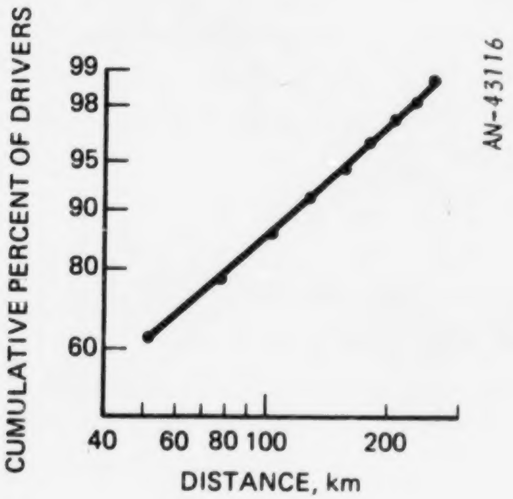

Figure 2. Distribution of Daily Driver Travel

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at single-family houses with off-street parking. There will be about one million such households in Los Angeles in 1980 having at least one secondary car. Thus, as shown in Table 3, the shorter-range electric car would be applicable to the functions of one million cars in 1980, or 17% of all Air Basin cars; but these secondary cars would be driven less than the average car and would account for a smaller proportion of area travel. The longer-range electric cars could generally replace automobiles where overnight recharge facilities will be available. In 1990, 3.1 million Air Basin automobiles are expected to be parked off-street at single-family houses, where recharging would be most easily arranged. In 2000, recharge facilities might be available at all of the 5.6 million off-street parking places projected at Los Angeles residences. These are the bases for the corresponding applicability projections in Table 3.

TABLE 3. APPLICABILITY OF ELECTRIC CARS

	1980	1990	2000
Cars, millions	1.0	3.1	5.6
Percent of all area cars	17	46	74
Daily Travel, km × 10^6	29	145	272
Percent of all auto travel	11	46	74

Provision of certain battery materials for the numbers of cars indicated in Table 3 could seriously perturb US metals markets. The nickel required for extensive regional use of nickel-zinc battery cars would require major increases in US nickel imports. The lithium for wide use of lithium-sulfur batteries would require a major expansion in US production facilities, but this problem is less serious: US reserves are adequate, and current production is modest.

Sources of recharge energy for electric cars were investigated through projection of future electric power production and consumption in the Los Angeles area, as shown in Fig. 3. The peak demand is anticipated on hot August afternoons, but even on the peak day demand is expected to fall dramatically in the late evening hours in the absence of car battery recharging. About 85 million kWhr, the shaded area in Fig. 3, would be available during the night of the peak 1990 day--more than enough to recharge the 3.1 million electric cars of Table 3.

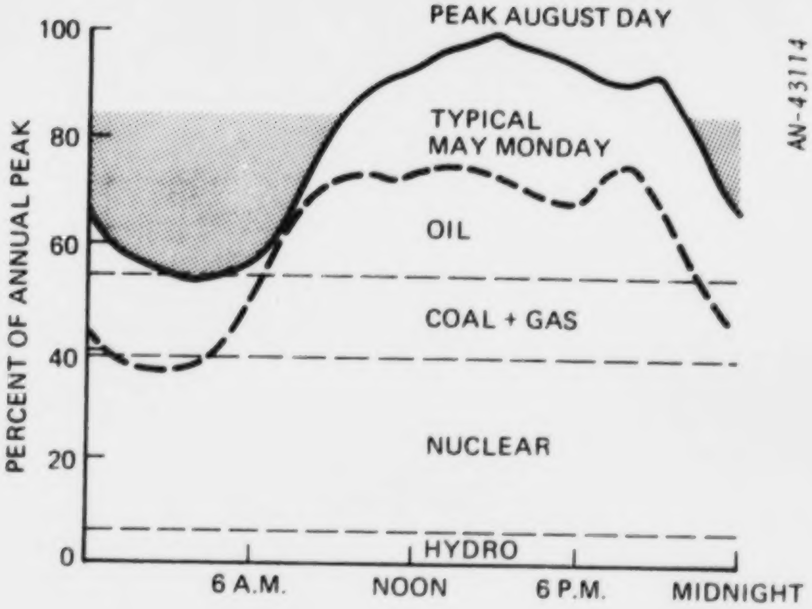

Figure 3. 1990 Electric Power Production and Consumption

Future peak power production is expected to grow at about 4 1/2% per year per capita in Los Angeles, and most of the new capacity is expected to be nuclear. Since use of existing oil-fired plants in the Air Basin will be more expensive and cause air pollution, Fig. 3 assumes oil-fired facilities will be used primarily for meeting peak loads, and so would be shut down in the late evening unless electric car recharging were in progress. On the peak day, petroleum would thus be the fuel for electric car travel. On low-demand days, however, such as the May Monday of Fig. 3, coal, gas, and nuclear fuel could provide recharge power; on an annual average basis, 46 percent usage of the efficient advanced-battery cars could enable a reduction in automotive petroleum usage of 37 to 44%.

Relative petroleum fuel consumption of the electric cars of Table 1 is shown in Fig. 4. The thermal efficiency of electric power generation is assumed here to be 36%, and the efficiency of electric power transmission to be 91%. All recharge energy is here assumed to be provided by oil-fired facilities. As the dashed line of Fig. 4 indicates, the fuel consumption of average ICE (internal combustion engine) cars in Los Angeles is expected to improve by 50% in this century, in line with legislation now being considered by the Federal government. The improvement would be achieved partly through improved technology and partly through a substantial reduction in average car

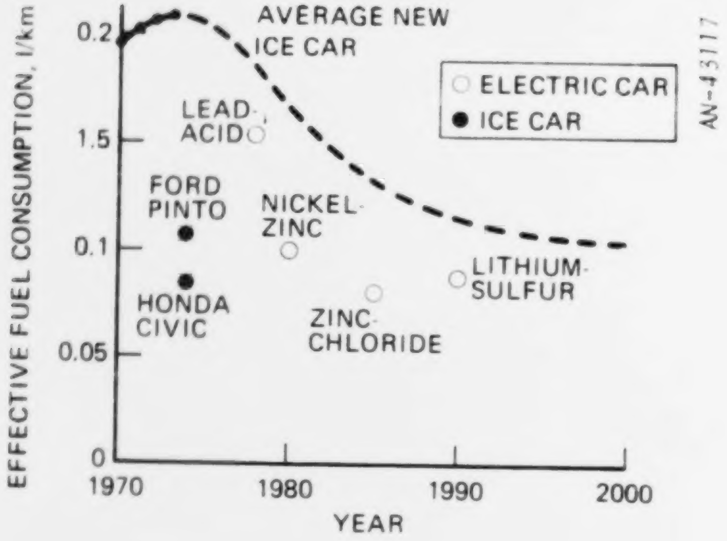

Figure 4. Auto Fuel Consumption

weight from its present level of 1600 kg. Fuel consumptions of ICE cars in Fig. 4 include a refinery energy penalty of 10%.

Relative to the average ICE car, Fig. 4 shows that electric cars promise reduced total energy consumption. The electric cars offer little or no energy savings, however, relative to existing ICE subcompacts of comparable size (and superior performance).

Electric car use can dramatically reduce emissions of key Los Angeles air pollutants. But as shown in Fig. 5, existing legislation requiring 90% reductions of conventional auto exhaust emissions in this decade will dramatically reduce conventional vehicular emissions, and make cars a minor rather than major contributor to total emissions. Under these circumstances, air pollution will no longer be a critical problem in Los Angeles, and electric cars will be able to make only minor reductions in its overall levels.

Table 4 shows worst-case air pollution projected for 1990 in relation to Federal air quality standards and 1970 measurements in Los Angeles. Concentration of secondary pollutants (ozone and NO_2) were estimated by application of a photochemical smog simulation to detailed emissions forecasts. Concentrations of remaining pollutants were estimated by linear rollback. The 1990 baseline projection (no electric cars) in Table 4 shows major improvements in air quality, after which even very high usage of electric cars will reduce secondary pollutant concentrations relatively little, and will raise sulfur

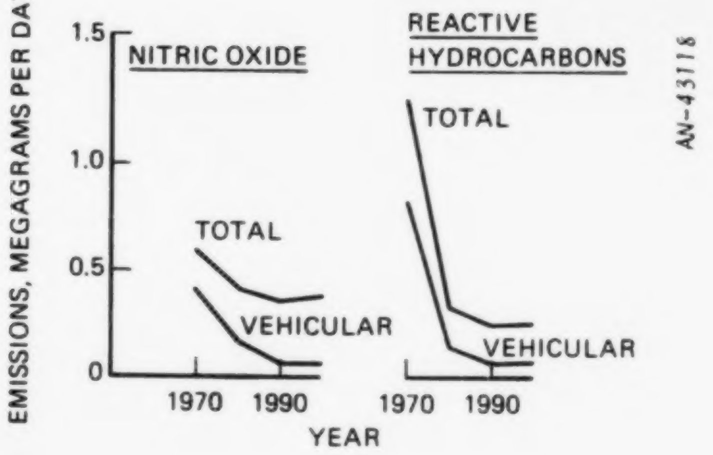

Figure 5. Projected Emissions of Air Pollutants Without Electric Car Use

TABLE 4. PROJECTED WORST-CASE AIR POLLUTION

Pollutant	Measure Units	Measure Period	US Standard	1970 Actual	1990 Baseline	1990 Change for 80% Electric Car Use
Ozone	pphm(1)	1 hr	8	62	15	-15%
NO_2	pphm	1 hr	-(3)	43	10	-20%
CO	ppm(2)	1 hr	35	54	7	-80%
SO_2	pphm	1 yr	3.0	2.6	4.1	+19%
Particulates	$\mu g/m^3$	24 hrs	260	357	437	-21%

(1) parts per hundred million

(2) parts per million

(3) No hourly standard is established. The annual average concentration standard is .05 ppm; the 1970 actual annual average was .063 ppm.

dioxide concentrations by similar amounts. Since worst-case air pollution occurs in late summer when electricity demand is highest, oil-fired recharging of electric cars is assumed, with consequent increases in SO_2 levels near coastal power plants.

Overall costs of electric car operation are projected in Table 5, together with costs of a conventional ICE subcompact automobile. The life of the conventional car is 151,000 km and 10 years; its initial cost is $2270, its fuel consumption is .078 liters per km, and it utilizes air pollution control devices with a significant initial and recurring cost. The electric cars are assumed to last for 12 years and 193,000 km. Their

TABLE 5. LIFE-CYCLE CAR COSTS

1973 cents per km

	Conventional		Electric Cars		
	ICE Sub-Compact	Lead-Acid	Nickel-Zinc	Zinc-Chloride	Lithium-Sulfur
Depreciation					
Vehicle	1.4	1.6	1.6	1.5	1.4
Battery	0	2.2-5.7	4.7	.5	.7-1.2
Upkeep	1.5	.9	.7	.7	.7
Fuel (ex tax)	1.1	.9	.6	.5	.6
Pollution Control	.6	0	0	0	0
Financing	.8	1.6	2.7	1.3	1.2
Taxes, Insurance, Parking, etc.	2.7	2.8	2.8	2.8	2.8
TOTAL	8.1	9.9-13.5	13.1	7.3	7.5-8.0

higher initial costs (see Table 1) are more than offset by longer life, lower maintenance, and reduced fuel costs. For the lead-acid and nickel-zinc battery cars, however, high battery depreciation costs make overall costs 22 to 66% higher than those of the conventional subcompact.

The higher costs of the nearer-term electric cars would significantly reduce consumer income available for non-transportation expenditures. Moreover, electric car use could cause significant dislocations in the Los Angeles area labor force. With 100% electric car use, 30,000-40,000 service station jobs would disappear, along with some 10,000-20,000 jobs in automobile service, parts, and sales businesses. The total job loss would be only partly compensated by increased employment in battery manufacturing. Overall, there would be a significant depressing effect on regional economic activity.

In conclusion, it appears that future electric cars could replace some or most Los Angeles automobiles with little sacrifice of urban mobility. Electric power facilities will probably be adequate for their nighttime recharge, and materials availability will pose major problems only in the case of very wide use of nickel-zinc battery cars. Air quality improvements due to electric car use will be relatively minor in importance, and total energy saving will be modest. Potential reductions in regional petroleum consumption for transportation are significant, however, and could be the most important benefit of electric car use. Until battery depreciation costs are dramatically reduced, electric car use will cause major increases in regional expenditures on automotive travel. Large-scale introduction of electric cars will also cause significant dislocations of regional employment.

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Na/S-Batteries as an Energy Source for Electrical Vehicles *

W. Fischer
Brown, Boveri & Cie AG
Zentrales Forschungslabor
6900 Heidelberg
Postfach 101332

It is shown by using experimental results of laboratory cells and by cost estimations, that Na/S-batteries may meet the technical and economical requirements of autotraction batteries. Furthermore, other applications, such as operating diving vehicles with such batteries, can be envisaged.

Des résultats experimenteaux et des estimations de coûts montrent, que des accumulateurs de sodium-sulfure peuvent satisfaire des besoins techniques et economiques pour des sources électriques d'automobile. En outre autres applications, comme par example la propulsion des sousmarins, avec ce type d'accumulateur sont possibles.

Aus Messungen an Laborzellen und aus Kostenschätzungen ergibt sich, daß Natrium/Schwefel-Batterien die an Autotraktionsbatterien zu stellenden technischen und wirtschaftlichen Anforderungen erfüllen können. Daneben sind andere Anwendungen, wie der Antrieb von Unterwasserfahrzeugen, mit Hilfe solcher Batterien denkbar.

Na/S Batteries as an Energy Source for Electrical Vehicles

Both, the shortage of oil resources and the air pollution problem have given new incentives to proof whether the battery powered electric vehicle may substitute today's gasoline powered vehicles, especially for city traffic. This goal can be achieved by finding cheap batteries of high energy and power density.

It is known that the relatively small energy density of the lead acid battery is the main obstacle in realizing electric vehicles with a sufficient range [1]. Therefore, all over the world, new electrochemical systems which are expected to give higher energy densities with correspondingly sufficient power densities are investigated [2].

Figure 1 shows results of an analysis made in the US for a 1000 kg electric car. Power- and energy density values, either already gained or expected, are compared with the requirements claimed for the energy source [3]. Curves showing various ranges and speed demonstrate that the demand for energy- and power densities increases with larger distances and higher speeds. The diagram shows that the energy density of the lead acid battery does not suffice to cover the minimum demand,

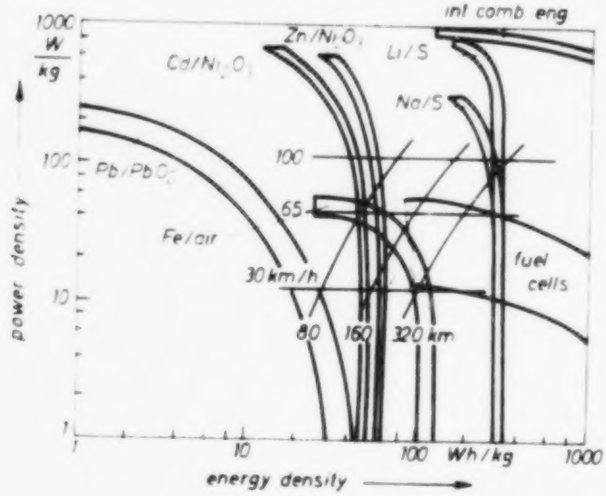

Fig. 1:
Power density and energy density requirements for a steady driving 1000 kg car superimposed on battery characteristics.

with regard to the range of city vehicles. Other conventional batteries (such as Ni/Cd-batteries) have higher energy densities but their specific price is also too high. Fuel cell systems have high energy densities - if liquid fuel is used - however, their power density is relatively low and presumably their specific price will be rather high. Therefore only the batteries shown on the right of the figure or alternative high energy systems will meet the requirements for vehicle operation.

Table 1: Theoretical Energy Densities (Wh/kg) of Electrochemical Cells

Metals Non-Metals	Li	Na	Mg	Al	Zn	Fe	H_2
F_2	6270	3590	4690	4080	1870	-	4100
Cl_2	2520	1330	1730	1330	750	660	1000
O_2	3240	1800	2850	2790	890	760	3670
S	2500	1290	1730	910	570	310	220
lead-accumulator: E_{th} = 160 Wh/kg E_{real} = 25 - 40 Wh/kg							

Table 1 shows the theoretical energy densities of cells which have particularly high values of energy densities. These values apply solely to the weight of the reaction substances and do not consider the weight of the other accumulator components such as the electrolyte, the case etc. Therefore, the actual energy density of the battery is lower than the theoretical value given in the table.

At the bottom of the table, theoretical and actual energy weights of the lead acid accumulator are given. It can be seen that the values deviate by a factor of 5.

The table shows that a number of electrochemical cells could be envisaged showing a higher density than that of the lead acid battery. Many of these cells cannot be realized for practical reasons. In some cases one of the reactants is gaseous and therefore needs quite a large volume. In other cases either very high temperatures are required to provide liquid (this means molten) reaction partners, or no adequate electrolyte for the system is known. The systems in table 1 marked with a thick line are those where experiments have already been carried out. One of these systems, the Na/S-battery, will now be discussed. About 12 different research groups in the US, Great Britain, France, Japan and West Germany [4] are investigating this system.

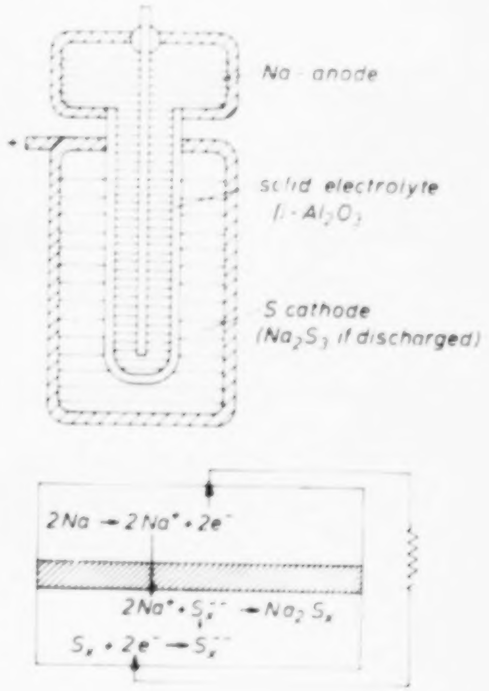
Na - anode
+
solid electrolyte
(β-Al_2O_3)
S cathode
(Na_2S_3 if discharged)
$2Na \rightarrow 2Na^+ + 2e^-$
$2Na^+ + S_x^{--} \rightarrow Na_2S_x$
$S_x + 2e^- \rightarrow S_x^{--}$

Figure 2:
Construction and Function of a Na/S-cell

In figure 2 a Na/S-cell is shown schematically. The two reaction substances sodium and sulfur are separated by a solid electrolyte. The electrolyte has the shape of a tube closed at one end. The reactants must be liquid to guarantee contact between the reactants and the electrolyte and a continuous electrochemical reaction. The operating temperature of the cell has to be about 300°C because this is a temperature higher than the melting points of the reactants and the reaction products. The problem of maintaining a contact between reactants and electrolyte applies also to other electrochemical cells, such as the lead acid accumulator, except here the electrolyte is liquid and the reaction substances are solid.

Figure 2 shows a charged cell. During discharging, sodium migrates as an ion via the sodium conductive electrolyte to the sulfur and forms sodium-sulfide. This lowers the sodium level and increases the sulfur level. During charging these reactions are reversed. The schematic diagram below the cell shows this reaction procedure in a little more detail: At the anode side sodium ions and electrons are formed from sodium. The sodium ions then migrate via the electrolyte to the cathode where they react with the sulfur ions and form sodiumpolysulfide. The sulfur ions are formed from sulfur and electrons. The electrons of the anode migrate to the cathode by producing electrical power in the load.

The crystal structure of this ceramic consists of spinal-like blocks which are formed by 4 layers of oxygen ions with aluminium ions in between. These blocks are connected to each other by oxygen bridges in relatively large distances. The sites between the bridges are only partly occupied by sodium ions. The sodium ions can migrate almost freely as ions in a liquid electrolyte. Therefore the ion conductivity of such a solid electrolyte is nearly as big as the conductivity of the best liquid electrolyte. The optimization of these solid electrolytes with regard to conductivity and life time is one of the main tasks of development.

There are other problems to be solved before Na/S-batteries can be produced. It is obvious that the reactants sodium and sulfur should not come into contact with air or with each other. Air would cause them to oxidize and in the case of contact with each other the reaction would be a chemical one and heat would be produced. Therefore the components of the cell must be connected tightly with each other. This is rather difficult because at 300°C the connection materials are subject to corrosion caused by sodium, sulfur or sodiumpolysulfide.

A Na/S-battery for practical application must contain many single cells for two reasons. The first reason is that a single cell produces only about 2V while a battery should have about 100 V or even more. Therefore, many cells must be electrically series connected. The second reason is that the waste heat released during charging and discharging of the battery must be used to maintain the operating temperature. For this purpose the battery must be insulated. Calculations have shown that the temperature does not drop below the melting point of the reaction substances when a 10 cm thick conventional insulation is around the battery, even when it is not operated for a whole day. Therefore, full power can be obtained after this period of time. For longer periods a better insulation or an external heat supply must be provided.

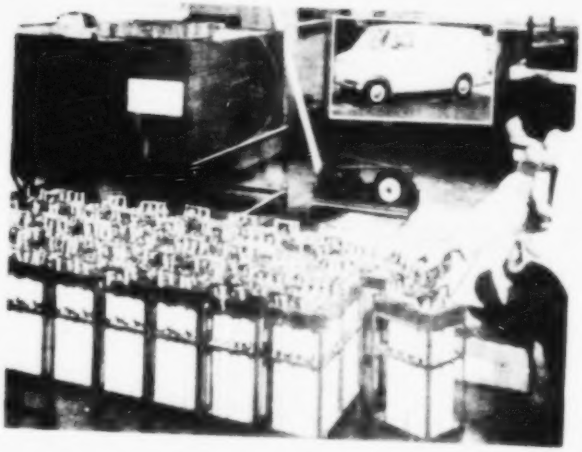

Figure 3:
50 kWh - 30 kW sodium-sulfur battery of the Electricity Council [5]

Figure 3 shows a prototype Na/S-battery built by the Electricity Council in England. In the foreground 400 single cells are shown and in the background the case which serves as the thermal insulation can be seen. The battery was mounted into a delivery van shown and has been used for a series of test rides in London.

Figure 3 shows that in principle, Na/S-batteries can be used for electric vehicles. To estimate the application possibilities more precisely, it is necessary to have technical and economical data of such a battery. In fig. 4 the estimated energy density and specific cost values of a 100 kWh Na/S-battery are compared with those of a lead acid battery. All components, including thermal insulation, have been considered. The diagram shows that these values depend on the time for discharging as well as on the size or the energy content of the single cell. To drive a vehicle, it is presumed that cells with an energy content of about 100 Wh/cell will be used. This corresponds with the lower energy density curve of figure 5 and the upper cost curve. When this fact is considered, it can be seen that the energy density of a Na/S-accumulator will be five times higher than that of the lead acid accumulator. The specific costs will presumably be lower than those of today's lead acid accumulators.

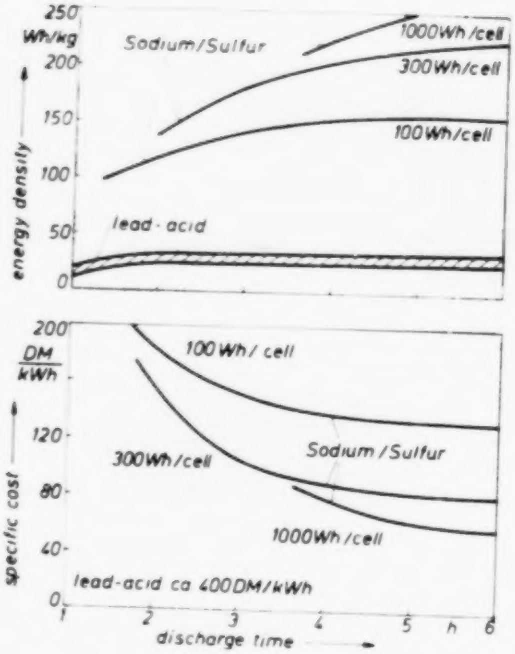

Figure 4:
Estimated energy densities and specific costs of Na/S-batteries

Values given in figure 4 allow comparison of weight, investment- and operation costs of electric vehicles powered with Na/S-batteries versus conventional gasoline powered vehicles. Fig. 5 shows the result of such a comparison with regard to operation costs arising per km. A battery capacity for 4 hours was assumed. The comparison was carried out for 3 types

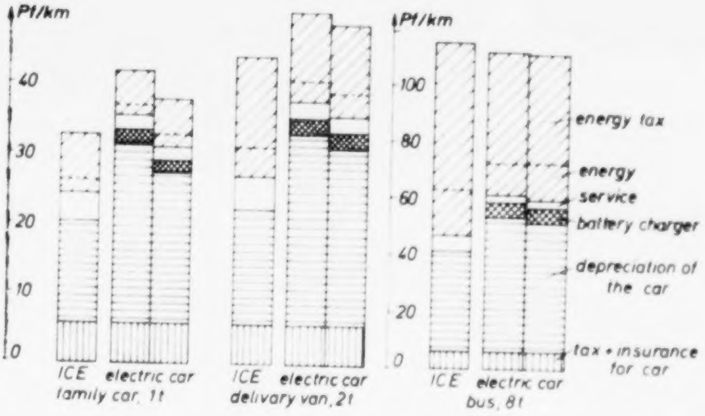

Figure 5:
Economy of gasoline- and electric vehicles

of vehicles: a passenger car, a delivery van, and a bus. For the electric vehicles two versions are considered. In the first version the power is regulated by thyristors, in the second version by a conventional gear shift. Costs per km include tax and insurance of the vehicle, depreciation of the vehicle and the charging station, running costs and energy costs. Since 2/3 of the gasoline prices are taxes a corresponding tax was added to the electric energy.

Analysis shows that the costs per km for electric passenger cars operated with Na/S-batteries are slightly higher and for busses slightly lower than those for conventional type vehicles. In general it can be said that within the error limits for such estimations, electric vehicles can be economical.

New accumulators with high energy densities should be considered not only for land vehicles but als for deep diving vehicles. Figure 6 shows a comparison of energy weights of various energy sources for deep diving vehicles. The diagram reveals that the "energy weight" of fuel using energy sources decreases with increasing time. The reason for this is that with long operating times the weight of the energy source may be neglected with regard to the fuel weight.

The energy weight of accumulators does not depend on the operating time.

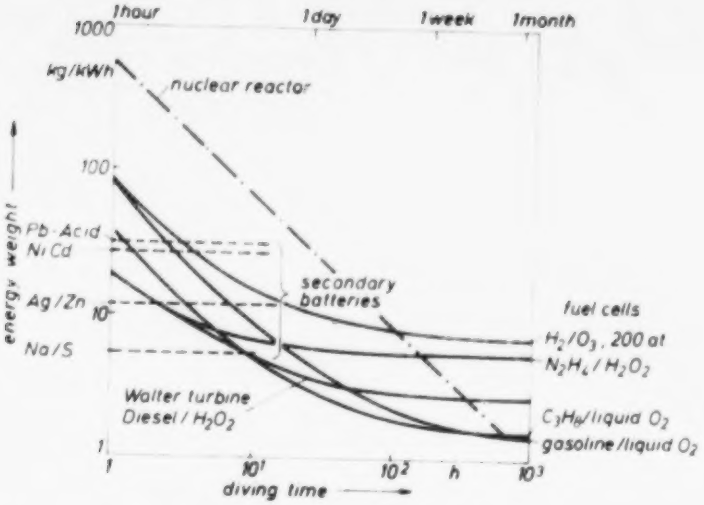

Figure 6:
Energy weight of power sources for underwater vehicles

Figure 6 shows that with regard to weight, Na/S-batteries are the most favorable up to a diving time of 10 hours. For higher diving periods the Walter turbine or fuel cell systems still to be developed would reveal even better results.

It can be concluded that several electrochemical systems may meet the requirements of a power source for electric vehicles. The Na/S-accumulator is one of the most promising systems.

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SESSION 4

Alternative Automotive Fuels

4ème SESSION

Nouveaux moyens énergétique
pour véhicules

THEMENGRUPPE 4

Alternative Kraftstoffe
für Kraftfahrzeugantriebe

Alternative Automotive Fuels - Status and Summary of In-Progress Research Activities

GRAHAM HAGEY
Environmental Protection Agency
Plymouth Building
2929 Plymouth Road
Ann Arbor, Michigan 48105

ANDREW J. PARKER, JR.
Richard P. Mueller & Associates
1900 Sulphur Spring Road
Baltimore, Maryland 21227

Present knowledge concerning alternative fuels as partial and complete substitutes to gasoline and distillates from petroleum for use in surface propulsion transportation systems, and the status of Federally-sponsored alternative fuels laboratory research performed by industry, government laboratories and universities are summarized. Work anticipated to be supported through Fiscal Year 1975 (July 1974-July 1975) that will augment and expand on current activities is discussed.

ABSTRACT

The objective of this paper is to summarize the present state of knowledge pertaining to the leading alternative fuels as partial and complete substitutes for gasoline and distillates from petroleum for use in surface propulsion transportation systems, and the status of Federally-sponsored laboratory research being conducted on alternative fuels.

The Federally-sponsored work is being performed by industry, government laboratories and universities. Work anticipated to be supported through Fiscal Year 1975 (July 1974-July 1975) that will augment and expand on current activities is discussed.

INTRODUCTION

Within the United States, Government sponsored advanced automotive propulsion system research and development activities have been expanded to include analysis and research on alternative fuels for gasoline and distillates from petroleum for use in surface propulsion transportation systems. In 1973 the Alternative Automotive Power Systems (AAPS) Division of the Environmental Protection Agency (EPA) initiated a program of study and applied research on alternative automotive fuels. Additionally, other Federal agencies are assisting in the combustion characterization of selected alternative fuels.

The goal of the Alternative Fuels Program is to evaluate the application of non-petroleum based fuels and energy sources as partial and complete substitutes to gasoline and distillates from petroleum for use in surface transportation systems.

The program by study and research provides for evaluation and assessment of the following fuels which have been determined to be the most promising future alternatives[1]:

- Gasoline-like fuels from non-petroleum energy resources, viz., gasoline and distillates from coal and oil shale.
- Unconventional fuels from non-petroleum energy resources, viz., methanol from coal and organic waste.
- Fuels from non-fossil energy resources, e.g., hydrogen.

The final evaluation and assessment will provide a relative ranking of the fuels and will, in the conduct of the evaluation, provide information on the characterization and future automotive utilization aspects of the fuels and their combinations. Thus, the program will provide appropriate information on the future fuels

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for automotive transportation such that rational public policy and technical choices can be made for the future introduction and use of the fuels.

DISCUSSION

In the United States, transportation consumes about 25 percent of domestic energy, and about 55 percent of the petroleum consumed is used by transportation.[2] In early 1974 consumption of automotive fuel was over 6 million barrels per day. This consumption relative to 1970 U. S. petroleum production of 11 mb/d[3] provides a strong motivation for Government agencies and the transportation industry to investigate the potential of alternative non-petroleum-based fuels for automotive applications. Several non-petroleum-based alternative fuels have been considered as potential replacements for, or partial supplements to, conventional petroleum-based fuels. These were evaluated on the basis of availability, compatibility with existing distribution and storage systems (both mobile and stationary), suitability for use with personal passenger cars, relative advantages in terms of vehicle fuel economy and emissions, costs to the consumer, capital investment costs, critical research gaps, technological status, and the time scale for production implementation. A principal data source used was two AAPS-funded studies (with the Institute of Gas Technology and Exxon Research and Engineering Company) related to the feasibility of alternative automobile fuels.

In evaluating the potential of alternative fuels for transportation, the energy source from which they are derived is a prime consideration. Domestic sources available in the future will be coal, oil shale, nuclear energy, and solar energy, while liquid petroleum and natural gas will be in continued short supply.[3] Significant production of liquid petroleum fuels from coal and oil shale cannot be expected until the 1985-2000 period.[1] Contributions to domestic energy needs from nuclear and solar energy are not expected to be available until even later periods for the mobile transportation sector.

Coal is relatively plentiful in the United States, but its availability will be limited by the mining rate. Oil shale resources are not as plentiful and domestic tar sands represent substantially lower fuel resources than oil shale.

According to estimates of the National Petroleum Council* and other sources, the domestic energy resource base for these fuels is 84 x 10^{21} Joules, equivalent to 1.43 x 10^{13} barrels of crude oil for coal and 10 x 10^{21} Joules, (1.70 x 10^{12} barrels crude) for oil shale. For coal resources, 41 x 10^{21} Joules, (6.95 x 10^{12} barrels crude) are proven and 43 x 10^{21} Joules, (7.34 x 10^{12} barrels crude) are reasonably assured. For oil shale resources, 12 x 10^{19} Joules, (2.07 x 10^{10} barrels crude) are proven, 1.6 x 10^{21} Joules, (2.70 x 10^{11} barrels crude) are reasonably assured, and 8.4 x 10^{21} Joules, (1.41 x 10^{12} barrels crude) are speculative. Recoverable reserves are less than the figures cited and depend largely on extraction economics, extraction procedures, and possible legal restraints.

Nuclear energy, if developed at the rate forecast, could indirectly benefit the transportation sector by partially relieving the electric sector from the use of fossil fuels. These benefits to the electric sector could also be supplied by solar energy. This energy source will require a major technology breakthrough to be of advantage to the transportation sector. It cannot be considered for the near-term period (1975-1985) and may be problematical for use to the year 2000.

Based on all the aforementioned considerations, it would appear that synthetic gasoline and distillate hydrocarbons manufactured from coal and shale will offer the greatest promise for contributing to automotive fuel requirements until the turn of the century. Coal-derived methanol (pure methanol or methanol-gasoline blends) is a potentially promising fuel if certain technical problems can be solved. Another alternative fuel of potential merit is hydrogen, but it can only be considered as a possible contributor to automotive needs in the period beyond the year 2000. The rationale for these selections is amplified in the following highlights which present the essential elements of the current status of leading alternative automotive fuels.

Synthetic Gasoline and Distillate Hydrocarbon Fuels

1. Synthetic gasoline and distillate hydrocarbon fuels could be manufactured from coal, oil shale, tar sands, or organic waste products. They possess the primary advantage of expected complete compatibility with existing and advanced

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*The National Petroleum Council is a U.S. industry advisory board to the Secretary of the Interior.

automotive powerplants, as well as with distribution facilities down to the local gas station.

2. Coal (particularly from strip mining processes) is by far the largest and most probable domestic energy resource available for synthetic fuel production, followed by oil shale. Additional domestic sources of much less potential, in terms of ability to meet projected energy needs, are tar sands and organic waste products.
3. The production cost in the post-1985 period for gasoline and distillate hydrocarbon fuels derived from oil shale is estimated to be competitive with that for current costs of conventional petroleum-based sources. Equivalent liquid hydrocarbon fuels derived from coal are more expensive. Waste product disposal constitutes a serious environmental problem in either case with processed oil shale being the most critical concern.
4. The production economics for liquid hydrocarbon fuels derived from coal and shale will ultimately depend on (a) the efficient commercialization of various production processes currently under evaluation in laboratory and pilot-plant models, and (b) the transport distance required for raw and/or refined products. Intensive capital investment will be required if several 50,000- to 100,000-barrel-per-day plants are to be in operation in the 1980-1985 period.
5. Little information is available on the actual use of synthetic gasoline or distillates in automotive engines. A test program to verify the compatibility of these fuels with automotive engines is planned for Fiscal Year 1975 under an interagency agreement between EPA and the Bureau of Mines.

Methanol

1. Pure methanol has seen limited successful use with spark ignition engines powering automobiles. It offers the following advantages:
   a. An increase in power from existing engines fueled with gasoline, largely because methanol heat of vaporization characteristics lead to increases in air inducted into the engine and to increases in net work output.
   b. An increase in efficiency and in power output per pound of engine weight for new engine designs because the

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engine can operate at higher compression ratios than with high octane premium gasoline.

Certain disadvantages of pure methanol will require that careful preparation by fuel distributors and automotive manufacturers precede its possible introduction into the retail sales market. Among these disadvantages are:

a. Fuel economy (in miles per gallon) with pure methanol is about half that with gasoline, necessitating a major increase in the size of the automobile fuel tank and modifications to the carburetor fuel jets.

b. When contrasted with gasoline, vapor pressure characteristics of pure methanol imply that there may be a greater incidence of vapor lock with current automobile fuel system designs. Also, cold start is more difficult and manifold preheating is required to ensure complete vaporization in carbureted systems.

c. Miscibility between pure methanol and water can result in the presence of water (from local atmospheric moisture) in the fuel distribution system, in the service station tanks, and in the vehicle tank, leading to possible corrosive action on metal surfaces in piping, tankage, and within the engine itself. Corrosion inhibitors may be required in the fuel to avoid this problem.

d. Synthetic methanol transport costs are expected to be higher than those estimated for synthetic gasoline because, for equal energy content, the pure methanol volume required to be piped, trucked, and stored is approximately twice that of gasoline. Therefore, when distribution costs are included, the cost at the pump to the consumer, per unit of fuel energy delivered (ex tax), is estimated to be about 25 percent greater than that for synthetic gasoline from shale and coal.

e. The solvent action of pure methanol may damage paint, metal, and plastic surfaces; therefore, solvent-resistant materials must be considered for use in all applications.

Methanol-Gasoline Blends

1. A greater near-term advantage may be evident by the use of methanol-gasoline blends rather than pure methanol. This approach would conserve gasoline stocks to a small degree without necessitating major redesign of automobiles or engines. It should be noted, however, that even if methanol is added in a methanol-gasoline blend only to the five percent level, current automotive fuel consumption would require about five times the present U.S. methanol production.
2. As with pure methanol, methanol-gasoline blends have a higher octane rating than gasoline alone. But there are indications that the motor octane number (MON) increase is not nearly as great as that which would be expected from measured increases in the research octane number (RON). This would indicate that engine road performance increases will not be as marked as those found in the laboratory.
3. Vapor lock and water miscibility problems would be present to a much greater degree with methanol-gasoline blends than with pure methanol. An example of these problems is the separation of gasoline and methanol in the presence of very small amounts of water, particularly at low temperatures. Solutions to these problems may be possible, but they require laboratory and road test verification.
4. The majority of published data on the application of methanol and methanol-gasoline blends to fueling automotive engines is about 20 to 30 years old. The use of new materials, engines, gasoline blends, and lubricating oils is a compelling factor for acquiring more contemporary characteristics of methanol in order to verify or invalidate older concepts regarding advantages and disadvantages of this alternative fuel. In this regard, the adaptability of methanol and methanol-gasoline blends to modern automotive systems will be explored systematically in a test program by the Bureau of Mines through an interagency agreement with EPA. Other research programs investigating methanol and methanol blends are in progress or planned at several universities and industry research laboratories.

Hydrogen

1. Success has been attained in carrying out the necessary mechanical conversions to enable conventional gasoline engines to operate on hydrogen. Indications are that extremely low exhaust emission levels are possible. Fuel economy on an energy-expended-per-mile basis is found to be better than that for gasoline, but maximum engine power output for a given engine size is reduced significantly.
2. A major technical drawback with hydrogen, as fuel for the automobile, is the problem of storage on the vehicle. In compressed gas form it is not practical, and even in cryogenic liquid form the complex and expensive storage requires a tank capacity three and one-half times that needed for gasoline on an equivalent energy basis. Research is underway to evaluate an alternative reduced-volume storage approach using metal hydrides; a means of also reducing the storage weight will be necessary before this technique can be considered practical.
3. Additional major obstacles to using hydrogen as a universal fuel concern the energy supply adequacy for its manufacture as well as very high costs to the consumer. Nuclear power will be a necessary factor in ensuring an adequate supply of energy for production of hydrogen by water electrolysis. On an equivalent energy basis, liquid hydrogen cost to the consumer will be much greater than the cost of gasoline or distillate derived from coal. Much of this cost is attributable to significant cost items connected with the liquefaction of hydrogen and its subsequent transportation to, and storage at, retail outlets.
4. Even if costs are reduced, hydrogen appears to be a possible fuel only for the post-2000 period. The massive capital requirements for manufacturing plants and distribution facilities, and the extensive period needed for actual construction activities, preclude any earlier consideration of this fuel as a major contributor to passenger car needs.

Information on production processes and logistic factors (including fuel costs) for the above alternative automotive fuels is provided in Tables 1 and 2 respectively.

TABLE 1. PRODUCTION PROCESSES FOR ALTERNATIVE NON-PETROLEUM-BASED AUTOMOTIVE FUELS

FUEL	PROCESS ALTERNATIVES	DEVELOPMENT STATUS	TECHNOLOGY NEEDS
GASOLINE/ DISTILLATE	1. COAL LIQUEFACTION 2. COAL GASIFICATION-SYNTHESIS GAS GASOLINE VIA FISCHER-TRIPSCH PROCESS 3. OIL-SHALE EXTRACTION	1. PILOT PLANT 2. COMMERCIAL PRODUCTION IN SOUTH AFRICA, INEFFICIENT, COSTLY 3. READY FOR COMMERCIAL PLANT	1. CATALYST, MATERIAL HANDLING HARDWARE DEVELOPMENT 2. MAKE MORE SELECTIVE, HANDLE CAKING COALS 3. DISPOSAL OF SPENT SHALE AND WATER, DEEP MINING TECHNIQUES
HYDROGEN	1. WATER-ELECTROLYSIS 2. COAL GASIFICATION-SYNTHESIS GAS (CARBON MONOXIDE PLUS HYDROGEN)-SHIFT CONVERTER-CARBON DIOXIDE SCRUBBER 3. THERMOCHEMICAL	1. COMMERCIAL PRODUCTION 2 PILOT PLANT 3. LABORATORY	1. IMPROVE CELL EFFICIENCY 2. EFFICIENT CARBON DIOXIDE REMOVAL, GASIFICATION PROCESS IMPROVEMENTS. 3. SIMPLE, ENERGY EFFICIENT CHEMICAL STEPS. AVOID CORROSIVE, UNSTABLE MATERIALS.
AMMONIA	HYDROGEN PLUS NITROGEN IN PRESENCE OF CATALYST	COMMERCIAL PRODUCTION WITH H_2 FROM NATURAL GAS	SAME AS FOR HYDROGEN ABOVE.
HYDRAZINE	1. RASCHIG PROCESS 2. UREA PROCESS	1. COMMERCIAL PRODUCTION 2. COMMERCIAL PRODUCTION	NEW CHEAPER PROCESS REQUIRED. THERMODYNAMICS LIMITS POSSIBLE SAVINGS.
METHANOL	COAL GASIFICATION-SYNTHESIS GAS (CARBON MONOXIDE & HYDROGEN) IN PRESENCE OF CATALYST	COMMERCIAL PRODUCTION DEMONSTRATED	GASIFICATION PROCESS IMPROVEMENT
ETHANOL	FERMENTATION OF AGRICULTURAL PRODUCTS (SUGAR, STARCH, CELLULOSE)	COMMERCIAL PRODUCTION	PRESENT FERMENTATION TECHNOLOGY TOO EXPENSIVE, NEED NEW RAPID FERMENTATION PROCESS
METHANE	COAL GASIFICATION-SYNTHESIS GAS (CARBON MONOXIDE PLUS HYDROGEN)-CATALYTIC METHANATION	COMMERCIAL PRODUCTION WITH METHANATION STEP NOW BEING DEMONSTRATED	GASIFICATION PROCESS IMPROVEMENT
PROPANE	BY-PRODUCT IN COAL GASIFICATION OR LIQUEFACTION	SAME AS COAL LIQUEFACTION AND/OR GASIFICATION	DEVELOP EFFICIENT BY-PRODUCT EXTRACTION FROM COAL PROCESSING

TABLE 2. LOGISTIC FACTORS FOR AUTOMOTIVE USE OF ALTERNATIVE NON-PETROLEUM-BASED FUELS

FUEL	EST. COST (1973 DOLLARS) AT PUMP (TAXES EXCLUDED) \$/10⁹ JOULES [a].	VEHICLE STORAGE	TOXICITY	SAFETY	COMPATIBILITY WITH PETROLEUM FUELS	STATUS OF DISTRIBUTION TO CONSUMER
GASOLINE[b]	2.99 (FROM COAL) 2.46 (FROM SHALE)	EXCELLENT	MEDIUM	HIGH FIRE HAZARD	--	EXISTING
DISTILLATE[b]	2.37 (FROM COAL) 1.90 (FROM SHALE)	EXCELLENT	LOW	LOW FIRE HAZARD	HIGH	EXISTING
LIQUID HYDROGEN	6.64 (FROM NUCLEAR ELECTROLYSIS) 4.46 (FROM COAL)	POOR	LOW	HIGH FIRE AND EXPLOSION HAZARD	LOW	MAJOR DEVELOPMENT AND INVESTMENT REQUIRED.
AMMONIA	7.25 (USING HYDROGEN FROM ELECTROLYSIS)	FAIR	HIGH	MODERATE FIRE HAZARD	LOW	SOME EXPERIENCE IN FARM DISTRIBUTION. MAJOR EXPANSION REQUIRED WITH EMPHASIS ON SAFETY.
HYDRAZINE	OVER 19	GOOD	HIGH	HIGH FIRE AND EXPLOSION HAZARD	LOW	MAJOR MODIFICATIONS TO EXISTING GASOLINE SYSTEM IN AREAS OF MATERIALS COMPATABILITY AND SAFETY.
METHANOL	3.22 (FROM COAL)	GOOD	MEDIUM	MODERATE FIRE HAZARD	HIGH IF WATER CONTAMINATION CONTROLLED	EXISTING GASOLINE SYSTEM COULD BE USED WITH MODIFICATIONS TO PREVENT WATER CONTAMINATION AND CORROSION.
ETHANOL	7.40 (FROM ORGANIC WASTE)	GOOD	LOW	MODERATE FIRE HAZARD	HIGH IF WATER CONTAMINATION CONTROLLED	SAME AS METHANOL.
METHANE	3.60	POOR	LOW	HIGH FIRE AND EXPLOSION HAZARD	LOW	ABOUT THE SAME PROBLEMS AS FOR HYDROGEN.
PROPANE	> 3.60 (FROM COAL LIQUEFACTION)	FAIR	LOW	MODERATE FIRE HAZARD	LOW	LIMITED AVAILABILITY AT PRESENT. REQUIRES EXTENSION.

[a] \$/10⁹ JOULES = DOLLARS PER BILLION JOULES FOR THE POST 1985 PERIOD.

[b] CURRENTLY, AT THE PUMP, GASOLINE FROM PETROLEUM AT 10.04 CENTS PER LITER IS EQUIVALENT TO \$3.08/10⁹ JOULES AND DISTILLATE FROM PETROLEUM AT 9.77 CENTS PER LITER IS EQUIVALENT TO \$2.65/10⁹ JOULES (TAXES EXCLUDED).

RESEARCH ON LEADING ALTERNATIVE FUELS

Federal Government sponsored research on alternative automotive fuels was initiated in 1974. This research includes work on gasoline and distillate fuels from coal and oil shale, methanol from coal, and hydrogen. Research activities are in their initial program phase and much additional research planning is in-progress.

Gasoline-Like Fuels

Gasoline and distillate fuels manufactured from representative coal and oil shale processing technologies will be characterized both as "pure" fuels and as blends with conventional petroleum derived fuels. In addition to standard properties characterization, the fuels will be combusted in a variety of internal combustion automobile engines for characterization of emissions, performance and fuel economy.

Depending on the degree of variability with conventional gasoline and distillate fuels, research may be undertaken on emission atmospheric effects, toxicity and materials research.

Methanol

Methanol manufactured principally from coal, and possibly from organic waste, will be characterized as "pure" methanol, methanol having some higher alcohols (e.g., ethanol) and as methanol-gasoline blends. Properties and engine characterizations will be conducted as for the gasoline-like fuels. Additionally, research on materials, toxicity, atmospheric emission effects and blend phase stability will be investigated. For pure methanol, research investigations are anticipated for modifications to internal combustion engine carburetors and induction systems to permit the combustion of methanol. Finally, it is anticipated that vehicle fleet testing will be conducted on both methanol-gasoline blends and pure methanol. Figure 1 shows the methanol research program tasks presently being conducted.

Hydrogen

Although hydrogen is a speculative fuel and widespread use in the automotive sector is unlikely before the year 2000, limited basic research is continuing on ways to effectively store hydrogen in an automobile. Storage research is principally focused on metal hydrides although liquid hydrogen carriers are also being investigated. Figure 2 shows the hydrogen research program tasks presently being conducted.

3 2

FIGURE 1-METHANOL RESEARCH

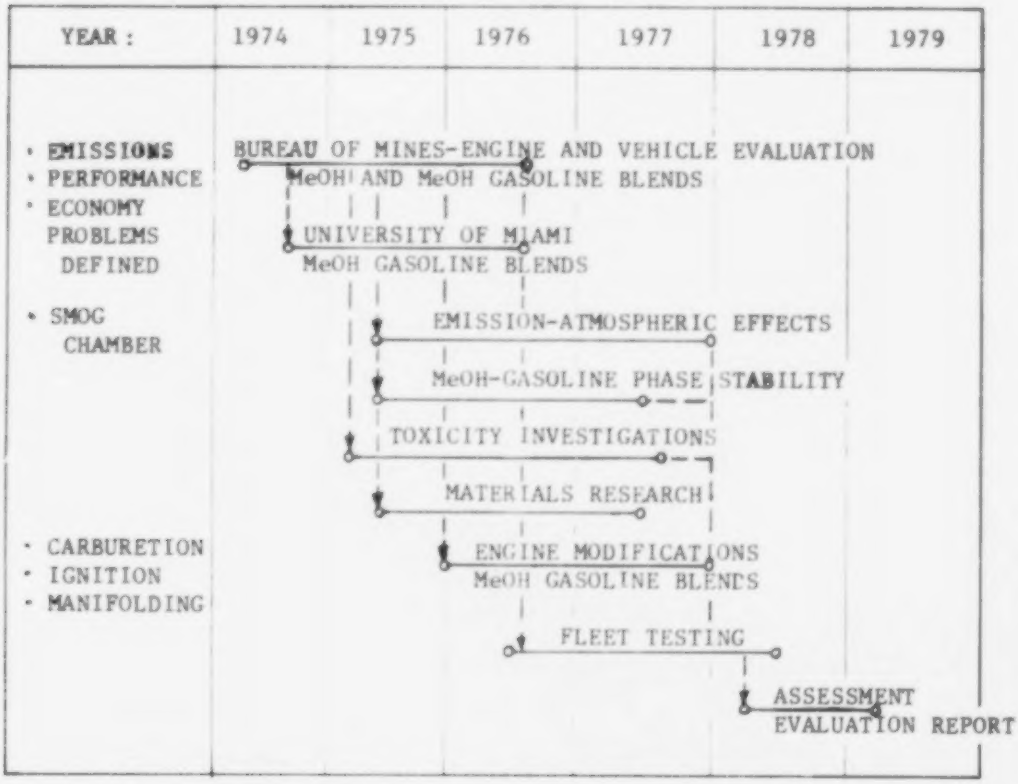
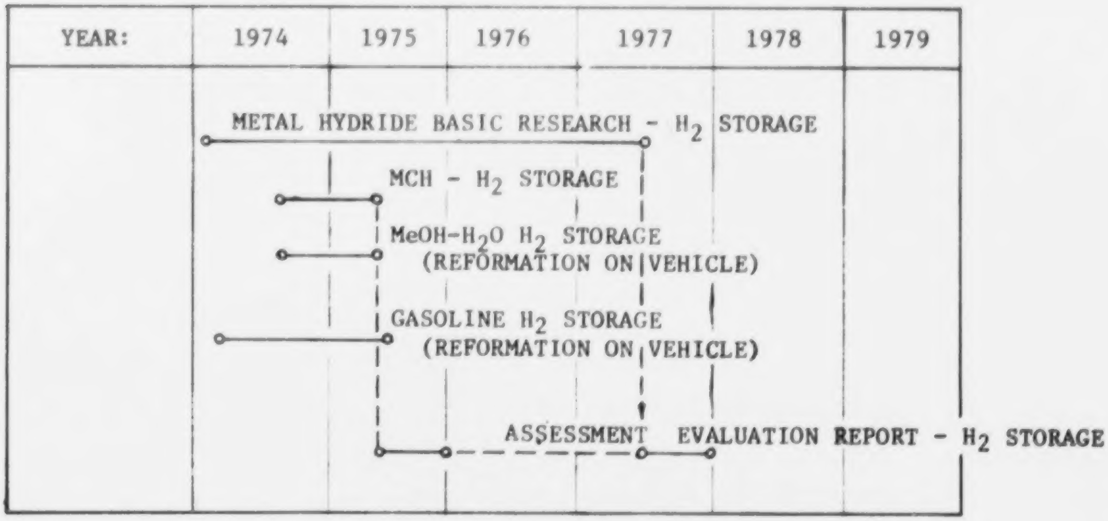


FIGURE 2-HYDROGEN RESEARCH



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Possible Alternative Fuels for Internal Combustion Engines with Regard to LPG and LNG

Dr.-Ing. E. Plassmann
Technischer Überwachungs-Verein Rheinland e.V., Köln

Based on a survey on the world energy reserves of fossil fuels and the use of petroleum as primary energy, we are going to analyze and evaluate the applicability of alternative fuels for the automotive sector in consideration of the energy situation in the Federal Republic of Germany.

Sur la base d'un exposé concernant les réserves mondiales en combustibles fossiles ainsi que l'emploi du pétrole en tant qu'énergie primaire et compte tenu spécialement de la situation énergétique en République Fédérale d'Allemagne uné analyse et une évaluation ont été faites sur la possibilité de l'emploi de carburants alternatifs.

Ausgehend von einer Übersicht über die Weltenergiereserven von fossilen Brennstoffen sowie des Einsatzes der Primärenergie Erdöl wird unter der besonderen Berücksichtigung der Energiesituation in der Bundesrepublik Deutschland die Einsatzmöglichkeit von alternativen Kraftstoffen für den Kraftfahrzeugbereich untersucht und eine Bewertung vorgenommen.

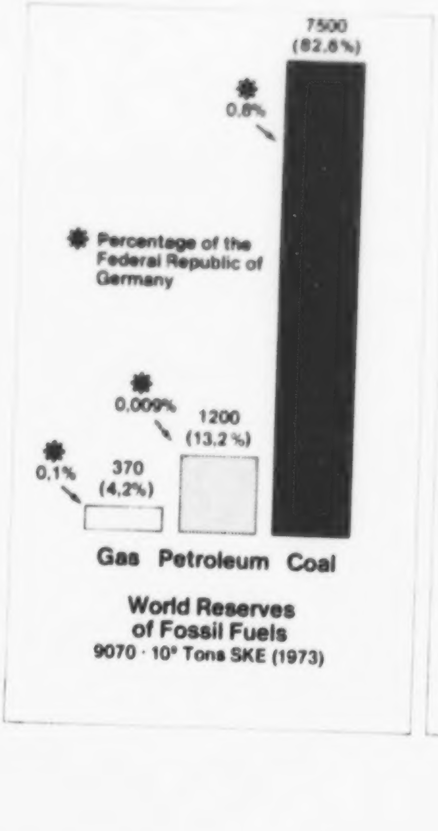
The fact that the energy crisis affecting the oil supply of the industrial nations has not yet been overcome, the present situation on the energy market and the disillusioning tenor of the treatise of the Club of Rome on the topic "The Limits to Growth" have caused all countries in the world to make every effort in securing the energy supply also on long-term basis by taking measures in respect of the energy policy and developing energy strategies.

Many countries in the world have declared that their common political aim is to attain a greater independence of foreign energy supplies, especially of the oil supplies from the Middle East. The European Communities intend to reduce the dependence on importations from 63 % to 40 % till 1985 and to 25 % till the year 2000 by restricting the energy consumption without reducing the economic growth, but with systematic utilization of domestic energy, especially of the nuclear power. On the basis of its new energy programme, the Federal Republic of Germany intends to reduce the share of petroleum in the primary energy supply from 55 % to 44 % till 1985.

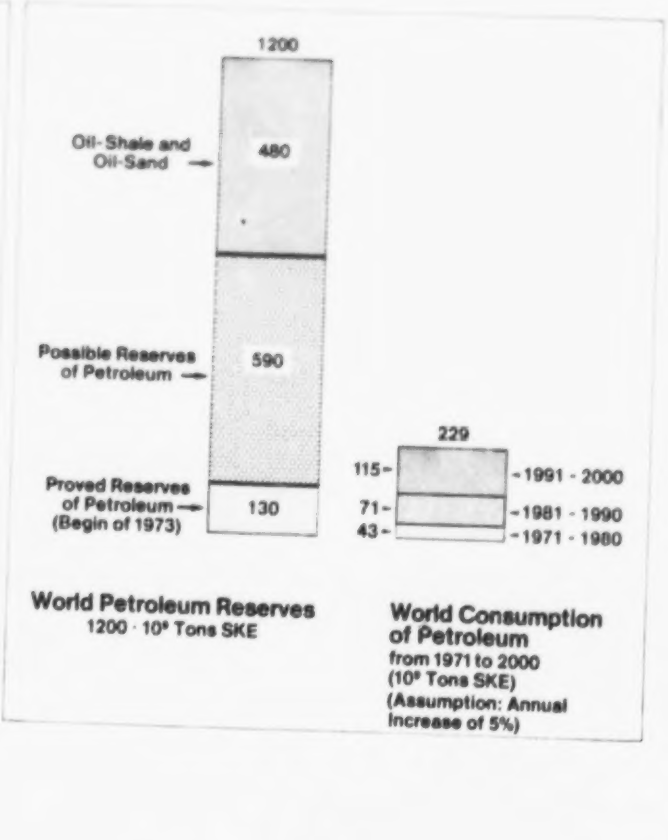
In view of the energy situation which is dependent on the political scene of action and an increase of the primary energy consumption to be expected, the question about the future availability of sufficient quantities of conventional fuels based on petroleum for the automotive application, is also raised in the Federal Republic of Germany.

In 1972, for example, approx. 55 % of the primary energy demand out of 354 million tons SKE were covered by mineral oil in the Federal Republic of Germany [1]. 19.3 % of this figure refer to liquid fuels for combustion engines. Various forecasts were issued on the development of the mineral oil demand till 1985. The growth rates range between 50 % and 70 % as compared to 1972.

Figure 1 shows a survey on the estimated world reserves of fossil fuels, such as gas, oil and coal, as well as a subdivision of the world oil reserves into proved, possible and other reserves (oil shale, oil sands) and the prospective development of world oil consumption till the year 2000 /2_7. The total reserves of approx. 9.070 billion (Brit.) tons SKE are subdivided into more than 82.6 % of coal, 13.2 % of oil, and 4.2 % of natural gases. The reserves in the Federal Republic of Germany with 0.1 % of natural gas and 0.009 % of petroleum are very low and inadequate for covering the national demand. However, with a share of 0.8 % of the world coal reserves (72.4 % of pit coal, 27.6 % of brown coal) corresponding to 60.8 thousand million tons SKE, the Federal Republic of Germany has enormous energy reserves /3 _7.



World Reserves of Fossil Fuels
9070 · 10^9 Tons SKE (1973)



World Petroleum Reserves
1200 · 10^9 Tons SKE

World Consumption of Petroleum
from 1971 to 2000
(10^9 Tons SKE)
(Assumption: Annual Increase of 5%)

This demonstrates that coal will play an important part in respect of the energy supply of the Federal Republic of Germany, especially in the case when high energy and cheap nuclear power heat may lead to better economy of the refining procedures of coal by using nuclear reactors for the generation of power on a larger basis [4].

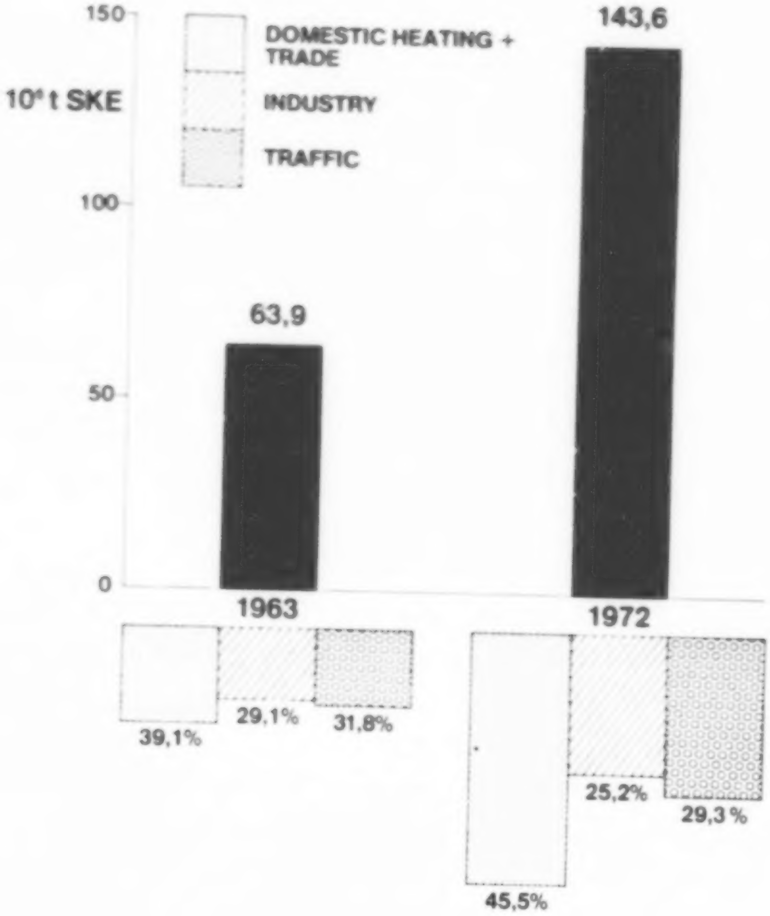
As regards the estimated oil reserves of 1.200 billion tons SKE (this figure corresponds to approx. 0.850 billion safe tons only 0.130 billion tons SKE or 10.6 % can be regarded as safe reserves in view of the present situation. For the time being, it is impossible to make any exact statements whether the possible oil reserves are worth being exploided etc. The question of economic production of oil from oil shale and oil sands cannot yet be judged definitely either.

Description of the world oil consumption from 1971 till 2000 shows the increasing shortage of the oil reserves and finally the demand which is far beyond the availability of proved oil reserves. If no further reserves are discovered or if the exploitation of oil shale or sands does not become possible on a larger technical scale in consideration of an adequate financial contribution by the consuming countries, noticeable shortage of the energy reserves of oil is to be expected from the mid-nineties.

This prospective development calls for investigations at the earliest possible time with regard to the measures to be taken for extending these oil reserves or whether whole consuming sectors (e.g. domestic heating, automotive traffic) have to pass over to other energy suppliers.

When dealing with such deliberations, numerous technological, economic, and last not least, political aspects will have to be taken into account, which, due to their complexity, aggravate the provision of long-term strategies. However, the possibilities and conditions are so different that they do not apply to each consuming country in general.

Fig. 2 shows the development of oil consumption in the Federal Republic of Germany during the period from 1963 to 1972 and the share of the three consuming groups in oil consumption i. e. domestic heating plus trade, industry and traffic /‾ 4 _7.



Consumption of Petroleum in the Federal Republic of Germany

Fig. 2 Consumption of Mineral Oil in the Federal Republic of Germany (Industry without power plants)

The growth rate of the group comprising domestic heating and trade amounts to 64 million tons SKE in the year 1972 (i.e. 125 % increase of consumption) and is overproportionate, whereas the consumption of industry and traffic increased underproportionately.

The traffic sector (motor vehicles, airplanes) claimed, in 1973, for example, 29 % of the petroleum importations of the Federal Republic of Germany, with a share of 16 % for gasoline, 11 % for diesel fuel and 2 % for jet fuel. Further 67 % were used for the production of fuel oil, and 4 % for the fabrication of bitumen [5].

The deficite due to the decreasing consumption of coal and the increase of the total energy consumption have almost been compensated for by the importations of petroleum. Accordingly the supply pattern of the Federal Republic of Germany has been subject to fundamental changes within a few years' time.

When developing strategies for securing energy supply which should be unsusceptible to crises and independent of importations as far as possible, the conditions should be evaluated under which liquid automotive fuels - nowadays generally based on petroleum - may be replaced by other energy suppliers, or the time should be determined when such substitution becomes compulsory.

Thus, the examination of so-called alternative automotive fuels is one of the most important tasks among the attempts to secure our future energy supply. Therefore, in view of the far future, alternative fuels should be manufactured economically, available at low costs, safe in operation, not hazardous as to toxicity, and more compatible with environment than today's fuels are.

Fig.3 gives a very schematic survey on the most important alternative fuels being discussed, i.e. synthetic gasoline, diesel fuel based on coal, liquefied petroleum gases (such as propane, butane), natural gas, methanol and hydrogen. Simultaneously, an attempt was made in this survey to evaluate these alternative fuels in comparison to the fuels in present use in consideration of crucial aspects like production, availability of raw materials, technology, load on environment and safety risks. This evaluation was one of the bases for an outlook on their applicability on a broad basis.

It must be pointed out that such a representation, simplified for clearness, may involve the risk of over- or underevaluation of certain problems.We are well aware of this risk, but believe that, today, stressing is inevitable to intensify the worldwide discussion on standards of evaluation and to recognize and initiate necessary developments which can be deduced from these standards.

		Gasoline/ Diesel Fuel		Liquified Petroleum-Gas (LPG)		Liquified Natural-Gas (LNG)	Methanol		Hydrogen
Production	Raw Materials	Petroleum	Coal	Petroleum	Coal	Natural Gas	Natural Gas	Coal	Water
	Comparable Energy Requirements for Production	Low	Very High	Low	High	Low	High	High	Very High
Availability of Raw Materials	Availability (Global)	Limited	Limited on Long Term Basis	Limited	Limited on Long Term Basis	Limited	Limited	Limited on Long Term Basis	Unlimited
	Import Dependence	Very High	Low	High	Low	High	High	Low	Very Low
Technology	Application in the Engine	Good		Good		Good	Good		Good
	Vehicle Storage	Simple		Difficult		Very Difficult	Simple		Very Difficult
	Additional Requirements on Infra-Structure (Transport, Distribution)			High		Very High	High		Very High
Load on Environment and Safety Risks	Load on Environment	High		Low		Low	Lower		Low
	Safety Risks	Low		Low		High	Low		Very High
Outlook	Chance for Application on a Broad Basis	Undoubted	Possible	Doubtful		Doubtful	Possible on Medium Term Basis		Possible on Long Term Basis

Alternative Fuels for Automotive Application

The applicability of synthetic gasoline and diesel fuel based on coal, respectively, must be regarded as doubtful though there is little dependence on importation and the technology of manufacturing is known in principle. The relatively large energy demand for production and the resulting problems of an economic application, connected with the heavy load on environment exerted by these fuels, undoubtedly show that methanol must be preferred to synthetic gasolines, provided coal supplies the primary energy for alternative fuels.

Today, liquified petroleum gases (LPG), such as propane or butane, are generally products of petroleum refinement in refineries, and usually an average output amounting to 2 % of the refinery capacity is assumed. A considerable portion (~1 %) of this liquefied gas production is consumed by various industrial branches, the remainder for domestic heating. Though the technical requirements for application of such liquid gases are fulfilled in principle, the limited availability is likely to allow only of restricted applications, e.g. taxis or similar applications.

The introduction of LPG based on coal as an alternative fuel is precluded by the large amount of energy required in production, the space wasted for storage in the vehicle as well as further motorial reasons. Therefore, methanol should also be given preference to liquid gases based on coal.

It is also unlikely that natural gas should be used on a broad basis as motor fuel, because its availability in the Federal Republic of Germany is considerably limited and its application for the supply of other consumers (e.g.domestic heating purposes) seems to be most important to reduce the load on environment. The complications due to storage of liquid natural gas in the vehicle raise additional problems.

As a result of the previous evaluation which takes special account of the energy situation in the Federal Republic of Germany, a broad applicability seems to exist only for the alternative fuels, namely methanol and hydrogen. This result has been found in a study on "Alternative Automative Fuels" issued just lately and made by 15 competent institutions of the Federal Republic of Germany on behalf of the Bundesminister für Forschung und Technologie (Federal Minister for Research and Technology) [6]. In this study, the fuels methanol and hydrogen are treated thoroughly and examined. They are regarded as the most promising alternatives during an experts' talk, considering all decisive aspects beginning with the abundance of the suppliers of primary energy and ending with their application in motor vehicles.

The study has the following results as to the application of methanol and hydrogen:

- The production of methanol and hydrogen from coal and water respectively in consideration of nuclear power waste heat seems to be possible in principle, therefore application of petroleum is no more required.

- Both fuels may be applied in combustion engines of known design as well as in novel engine systems,

- A stepwise change-over from gasoline to methanol and/or hydrogen seems to be possible in any case.

- The load on environment caused by detrimental byproducts of engine exhaust gases will be considerably reduced by the application of these alternative fuels.

It can be deduced from these premises that methanol may be a short- or medium- term substitute for gasoline, especially, if a change-over had to take place instantly. In a long-term view the problem of its dependence on restricted fossil raw products like coal or natural gas will arise. Thus, at long term, only hydrogen can be expected to be a general substitute for the conventional fuels, unless further raw materials containing carbon are applicable for the production of methanol or similar fuels.

Both alternative fuels - especially methanol - being applicable in mixed operation together with conventional fuels in combustion engines, a stepwise introduction of methanol and, later on, of hydrogen is conceivable and would decrease the consumption of petroleum as primary energy supplier. By this way, a smooth transition from fuels based on petroleum via a methanol technology towards a hydrogen technology would be considerably facilitated.

Alternative Fuels -- Methanol

R. W. Hurn
Bureau of Mines
Bartlesville Energy Research Center
P. O. Box 1398
Bartlesville, OK 74003

Methanol is identified as a viable option for an alternative motor fuel for use in spark ignition engines. The material may be used either as straight methanol fuel or blended with gasoline. In either form of use, methanol offers possible advantage but only coupled with significant problems. Combustion characteristics may be improved, but materials compatibility and blend phase stability present serious difficulties. An experimental program to more comprehensively describe the physical and combustion characteristics of methanol and methanol/gasoline blends is described.

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ALTERNATIVE FUELS -- METHANOL

R. W. Hurn
Bureau of Mines
Department of Interior

ABSTRACT

Methanol is identified as a viable option for an alternative motor fuel for use in spark ignition engines. The material may be used either as straight methanol fuel or blended with gasoline. In either form of use, methanol offers possible advantage but only coupled with significant problems. Combustion characteristics may be improved, but materials compatibility and blend phase stability present serious difficulties. An experimental program to more comprehensively describe the physical and combustion characteristics of methanol and methanol/gasoline blends is described.

INTRODUCTION

This is intended as a brief report of the background and current status of the Bureau of Mines research-oriented interest in utilization of methanol. Except as they relate to the background for this study, the technology for manufacture of methanol and related issues concerning potential supply and availability are outside the scope of this work. The discussion will (1) cover results from a small amount of experimental engine work that has been done at the Bartlesville, Oklahoma, Energy Research Center, (2) will identify both advantageous and potentially troublesome physical and combustion characteristics of methanol, and (3) will conclude with an outline of an experimental program that is projected beginning in early summer 1974 and carrying into the summer of 1975

About 1972 there began to emerge a consensus among the Bureau's energy specialists that conversion of coal offered the most promising alternative to historical and traditional sources of liquid fuel for use in transportation. The 1972 consensus appears valid in 1974 when, if the question of an alternative liquid coal conversion product is put in the context of immediate or near-term availability in large scale production, then the options are reduced to one, and that is methanol. At most the option would be no broader than to cover alcohol-type derivatives of coal gasification. The argument that supports this assessment of the situation is commandingly simple:

(a) In the fall of 1973 and the summer of 1974 in comprehensive reviews (1-2)[1] of the status of conversion technology, spokesmen for several major process design and engineering construction companies reported capability to proceed with design and construction of plants to produce methanol from coal, while,

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[1] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

(b) the same review sessions yielded solid consensus that the technology for production of coal-derived liquids via direct coal liquefaction was at least four or more years away from the earliest time for committal to plant design and construction.

Having narrowed the options the question arose -- if methanol is to be used to supplement liquid fuel supplies, then in what application would it be used? Basic engineering considerations led to the judgment that if methanol were to be used, it could be used most advantageously as fuel for stationary power systems including boilers and gas turbine power units. It was recognized however, that significant conversion to an alternate fuel by any category of users would involve complex logistic, supply, economic, and even political considerations. Therefore, any simple assumption assigning methanol to stationary systems would be arbitrary, and it appeared prudent to launch an experimental study in the use of methanol for transport power.

AN EXPLORATORY EXPERIMENTAL STUDY

To begin the experimental study the first decision was upon the question -- in what form should methanol be used? Is it more advantageously used as straight methanol fuel or as a blending component of gasoline? On this question first preference appears to be for use as straight methanol in vehicles in fleet service. Second preference would be for use of the alcohol as a blending component of gasoline. The rationale for this position rests primarily in two arguments: (1) blending methanol with gasoline poses very difficult problems both in distribution and in satisfactory control of fuel physical and combustion properties that are significantly affected by the addition of methanol to gasoline, and (2) while straight methanol could be an excellent motor fuel, its solvent, chemical, and physical properties are not fully compatible with materials and design of conventional automotive equipment. These factors considered, the use of straight methanol might be the preferable use provided it were limited to fleets in which the special requirements for use of methanol could be met in systematic, uniform modification of fleet units and service facilities.

Emissions and Fuel Economy - Methanol

Inasmuch as straight methanol appeared to be the preferred form of use (by the estimate of the Bureau's automotive technology experimentalists), the initial experimentation was made with the fuel in this form. Experimental work was first done using a single-cylinder CFR engine to outline the limits of air-fuel ratio with which acceptable engine performance could be achieved. Results of this work indicated that combustion of methanol might be sustained at air-fuel (A/F) equivalence ratios[2], extended far into the lean region. From this it was deduced that attractively low levels of hydrocarbon (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x) emissions might be realized via utilization of the fuel in very lean mixture combustion. Following work with the CFR engine, experimentation was transferred to a multi-cylinder, high production, U.S. V-8 engine operated on a dynamometer stand. Difficulties in carburetion of the fuel with the standard carburetion equipment were immediately apparent and were not satisfactorily solved for the duration of experimentation with this particular engine and its accessory package. Nevertheless, as will be explained, some useful data were obtained in steady-state tests with the engine.

The more severe operational deficiencies were encountered in attempting to execute the transient modes of simulated traffic cycles. The nature of the difficulty -- stumble, loss of power, and generally poor and erratic throttle response -- clearly indicated carburetion and mixture distribution problems. Operation at steady-state, however, was relatively stable. Experimental data on fuel economy and emissions were therefore taken at steady-state; illustrative results (tests at 50 mph) are shown in figure 1. In these data, the relationships of emissions to stoichiometry are much the same as is to be found with gasoline except for two features -- extended lean misfire limit and high aldehyde yield. As will be discussed in some greater detail, problems in mixture distribution were suspected and may have been largely responsible for the high level of aldehydes. However, accountability for the high aldehyde yield is by no means established, and this emissions aspect of methanol combustion will be closely observed in future work. At present it can only be said that aldehyde emissions may be a problem with methanol.

With respect to the lean combustion limit, from experience with single-cylinder engines it was expected that the multi-cylinder engine could be operated at air/fuel equivalence ratios as lean as 1.6 to 1.8. This proved not to be the case, however, as acceptable operation was limited to a lean limit of about 1.3 to 1.4 equivalence ratio calculated for the composite exhaust. It was postulated that inability to extend operation to the expected lean-limit could be due to fuel maldistribution. This possibility was tested by sampling individual cylinders for combustion products from which the mixture ratios were computed for the individual cylinders. Serious maldistribution was found, table 1. These data indicate that, compared with gasoline for which the maximum equivalence ratio spread between cylinders was 0.07, the comparable spread found when using methanol was over double that for gasoline, or 0.16, at a moderately lean fuel setting and

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[2] In this paper an equivalence ratio value greater than unity indicates a fuel lean (excess air) mixture.

TABLE 1. - Methanol fuel maldistribution 8-cyl. 350-CID engine

		Max. spread between cylinders	
	Stoich. A/F	A/F	Equiv. ratio
Gasoline.........	14.55	1.06	0.07
Methanol.........	6.46	1.06	.16
Methanol (lean)...	6.46	1.21	.18

0.18 near the limit of lean adjustment at which the engine could be operated. Extrapolation of this spread to the other test data would indicate that at a lean limit of 1.4 average equivalence ratio some cylinders could be operating at close to 1.6. This value is in acceptable agreement with the lean-limit determined from work with the single-cylinder engine, and its association with the multi-cylinder operation adequately explains the lean limit behavior as observed.

In addition to the work discussed above, attempts currently are being made to outfit a test engine or a vehicle that when using methanol will operate satisfactorily through transients and over a full driving range. The approach has been to accomplish this without dependence on full fuel vaporization in the carburetion process because the heat requirement for vaporization of the methanol is very high -- more than seven times that of an amount of gasoline of equal energy content. The transfer of this amount of heat is not readily accomplished by adaptation of conventional induction hardware and it was thought preferable to attempt some version of fuel injection or carburetion of finely dispersed fuel droplets. Effort along this line of approach is being continued. Prognosis is uncertain but if methanol is to be used in reciprocating spark-ignition engines, there clearly is a pressing need for development of a fuel/air metering and distribution system for this fuel.

Emissions and Fuel Economy -- Methanol/Gasoline

The scope of the experimental program was expanded to include methanol/gasoline blends when it became evident that there was significant interest in considering methanol primarily as a supplementary component in fuel blending. In order to have information directly available from the Center's experimental program with which to answer both official and unofficial queries on the subject, a limited amount of work was done with gasoline/methanol blends. From the outset, results of this work were to be considered as grossly inadequate for assignment of performance characteristics of methanol. Notwithstanding, it was felt that the results would be useful in indicating directional trends and thereby provide a basis for judgment and decision on the justification, if any, for further work with alcohol as a blending component. Experimental data were therefore obtained on four 1972 to 1974 model cars, table 2.

3 4

TABLE 2. - Fuel economy using methanol/gasoline fuel

	Driving pattern			
	Highway		City	
	Miles/ gallon[1]	Miles/equiv. gallon[2]	Miles/ gallon	Miles/equiv. gallon
Gasoline......	17.7	17.7	13.0	13.0
10 pct MeOH...	17.1	17.9	13.5	14.1
20 pct MeOH...	16.7	18.2	12.9	14.1

[1] Volumetric basis -- miles per gallon of fuel, gasoline or blend as applicable.

[2] Equal energy basis -- normalized to equal energy content per unit of fuel used -- base value, gasoline.

It was found that on a volume basis highway route fuel economy decreased as alcohol was added to the gasoline; city route economy rose with addition of 10 pct methanol but fell with 20 pct. In terms of the energy content of the fuel, economy improved with addition of alcohol as measured both in highway and in city driving.

Although no data were taken to measure cycle A/F ratio, the emissions data, table 3, would indicate that the addition of methanol effectively leaned the mixture. More specifically, with the addition of 10 pct methanol, CO emissions decreased from over 35 to less than 25 grams per mile and further decreased to about 15 grams per mile with addition of 20 pct methanol. Hydrocarbon emissions were virtually unchanged between the gasoline and methanol blends. Nitrogen oxide emissions were unchanged between gasoline and 10 pct methanol, but decreased measureably with the addition of 20 pct methanol. The simultaneous decrease of CO and NO_x indicates extension of A/F into the lean region and is consistent with behavior as would be deduced from the emission trends as shown in figure 1.

TABLE 3. - Methanol/gasoline emissions--city route, 4 cars

	Fuel economy, miles/equiv. gallon[1]	Emissions, grams/mile		
		CO	HC	NO_x
Gasoline.......	13.0	35.5	2.9	3.6
+ 10 pct MeOH..	14.1	24.4	2.7	3.7
+ 20 pct MeOH..	14.1	15.5	2.8	3.2

[1] Equal energy basis -- normalized to equal energy content per unit of fuel used--base value, gasoline.

On the basis of these data it appears that the effect of methanol addition on CO emissions and on fuel economy is primarily -- and almost exclusively -- an effect that results from the alteration of fuel/air stoichiometry. An additional effect on NO_x may derive from lowering combustion temperature by introducing the relatively inert mass of the OH radical as a component of the fuel.

3 4

THE PROPERTIES OF ALCOHOL FUELS

Octane Quality

Very high blending octane value has been cited for methanol but regrettably the high value is recognized principally in the research octane rating and not in the motor octane rating that more closely predicts the knock characteristics of fuels when used in late model U.S. vehicles. The data of figure 2 showing blending octane values for 10 and 20 pct methanol in unleaded Indolene[3/] are illustrative of this difference in motor and research blending octane number. Whereas at the 10 pct addition level, methanol has a blending value close to 140 research octane number, its motor blending value is only about 105. Much more detailed information on blending value for various gasoline stocks is requisite to any fully useful evaluation of the anti-knock value of alcohol. Nevertheless, on the basis of information currently in hand it does appear that the anti-knock quality of the material will be seriously overrated if judged on the research rating alone.

Vapor Pressure of Gasoline/Methanol Blends

One of the more serious problems in blending methanol with gasoline is its effect on vapor pressure of the mixture. The addition of a small amount of methanol to a typical gasoline will result in a vapor pressure for the blend increased by several pounds over the vapor pressure of the base gasoline. This is due to the non-ideal solution characteristic of the blend; when in solution with gasoline the intermolecular hydrogen bonding of the hydroxyl radical is weakened and equilibrium vapor pressure is correspondingly increased. The effect is illustrated in figure 3, showing that with addition of 10 pct methanol a 12-lb RVP fuel has its vapor pressure increased to a value above 14 lbs. It follows that if methanol is used as a gasoline blending component, then the traditional high vapor pressure fuel components must necessarily be withdrawn in part, i.e., not used or used in lesser quantity than is typical in current fuel practice. Adjustment to a new material balance in blending fuels would not be outside the capability of modern refining technology but redistribution of product, e.g., finding use for displaced butane, could pose serious problems in balancing refinery streams and, overall, might entail significant manufacturing cost penalty. Those problems aside, the effect of methanol on gasoline vapor pressure would most surely rule out the feasibility of random addition of methanol to supplement available motor fuel supplies.

[3/] A proprietary fuel widely used in the U.S. as a baseline or standard fuel in automotive testing.

While elevated vapor pressure poses a problem in connection with blending gasoline and methanol, vapor pressure that is too low may be a problem in using straight methanol. In this case the vapor pressure of methanol, less than 4-lb RVP, could be an exceedingly difficult factor in designing fuel metering systems for satisfactory engine starting and warmup. Assuming use of a modified but essentially conventional carburetion system this problem could be alleviated somewhat by the addition of a small fraction of high vapor pressure hydrocarbon to methanol. Although the solution vapor pressure effect is not so dramatic on the methanol side of the binary mixture, there can be nonetheless, a pronounced increase in vapor pressure by addition of hydrocarbon. The effect is illustrated by the data of figure 4; addition of a lighter material such as butane or isopentane would have a much greater effect than that shown for the 12-lb RVP gasoline.

Miscibility of Gasoline and Methanol

Methanol has limited solubility in most gasolines and miscibility of the two is further reduced drastically by the presence of water. The mechanism of this is that with only a small amount of water present, methanol will be extracted from the methanol/gasoline solution into a separate water/alcohol phase. The amount of water that can be tolerated without phase separation will vary with temperature, with the composition of the gasoline, and with the amount of alcohol in the blend. As a practical matter, however, water tolerance will be limited to a small fraction of 1 pct if methanol/water phase separation is to be avoided. The effect of phase separation is twofold --

1. Migration of alcohol into the water phase strips the alcohol from the fuel thereby altering the fuel characteristics and possibly representing unrecoverable loss of fuel (as would be the case in discarding water bottoms), and,
2. Separation in a vehicle fuel system can result in introduction of predominantly alcohol/water mixture into the carburetor. This might be tolerated in a warm, running engine but might also cause serious stumble and surge reaction. If the introduction occurred during an attempted start, the result would almost certainly be total operational failure. Water tolerance is reduced sharply as temperature falls.

Even with an essentially dry system, solubility of methanol in hydrocarbon can be a problem. It is soluble to the greatest extent in aromatic, has least solubility in normal paraffins, and has intermediate solubility in unsaturates; with all classes, solubility decreases with increased molecular weight of the hydrocarbon. At temperatures above 70° F dry methanol would be found typically miscible in all concentrations with an aromatic gasoline but probably less than

15 pct would be soluble in a low aromatic (15 pct) fuel. Below 20° F with only traces of water present, solubility is virtually negligible in all except highly aromatic fuels.

More information on miscibility is needed but it is even now evident that the problems associated with water tolerance and phase separation constitute a formidable barrier to wide-scale use of methanol as a blended motor fuel component.

Compatibility of Methanol with Engine and Fuel System Components

Materials compatibility problems with methanol could be substantial. Chief among the areas of concern are corrosion, elastometer swelling, and incompatibility with sealing agents. Increased engine wear has been reported for some tests with alcohol fuels. Further exploration of these factors are beyond the scope of this paper, but in any consideration of the use of methanol, existence of these problems -- some potentially serious -- should be recognized.

PROJECTED EXPERIMENTAL PROGRAM

The foregoing will have indicated the nature of some problems in utilization of methanol. The experimental program projected for the latter half of 1974 and into 1975 primarily would extend the experimental study along the lines already indicated. For purposes of classification the studies can be placed in three categories,

(1) determination of the physical and combustion properties of alcohol/gasoline blends including all of those properties that significantly affect its use in engines including handling in all phases of supply/distribution,

(2) determination of fuel economy and emissions data from a cross section of automotive equipment in order to enable more reliable estimates of the results to be expected in wide-scale use of methanol and methanol/gasoline blends, and

(3) the identification and assessment of the severity of operational problems that might be met in attempting to use alcohol or gasoline/alcohol blends in conventional automotive equipment.

The experimental program to develop comprehensive data on the physical and combustion properties of gasoline/alcohol blends will be conducted using eight base gasoline stocks. These stocks will be prepared with aromatic content at four levels (ranging between about 15 and 35 pct) for each of two octane levels -- targeted at 83 and 89 motor octane number for 5 pct alcohol blends.

The data to be obtained on each of the blends include the typical motor fuel inspection data including distillation, vapor pressure, and gravity, plus laboratory octane ratings. Some road octane ratings will be obtained.

Fuel economy and emissions data are to be obtained in an experimental program currently projected to involve a total of ten 1974 and 1975 vehicles, two prototype engines, and alcohol/gasoline fuels blended at two or more levels of alcohol content. The vehicles will in most instances include paired catalyst and non-catalyst emission control systems.

The segment of the experimental program to identify operational problems with methanol fuels will be run using three laboratory-based vehicles operated over pre-selected city routes. One of the vehicles will be fueled with methanol -- two with a 10 pct gasoline/methanol blend. These vehicles will be in test operations on a full time basis with close surveillance of incidence of water/alcohol separation from fuel, operating A/F, emissions, fuel economy, and possible deterioration of any mechanical or sealing component in contact with fuel.

In addition to work with the laboratory-based vehicles, it is intended that fleet tests of alcohol/gasoline blends be run using 30 to 40 units of employee-owned vehicles. Operators of the lab-based vehicles will provide detailed information on starting, driveability, stall or stumble, and other vehicle operational characteristics that could be identified with fuel property. Operators of vehicles in the fleet test will be expected to report on such operational problems as vapor lock, impaired driveability, or starting difficulty.

In short, the experimental program is designed to obtain experience in working with both methanol and with methanol/gasoline blends in order that fuel technologists may have information from which to better assess the potential that methanol holds for advantageous use as a supplemental fuel. At the same time, it is hoped that the program will provide information on operational problems that might be encountered if methanol were to be used either by virtue of voluntary election of that option or as a result of being forced to use methanol as a matter of emergency need to supplement available motor fuel supply.

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2. Methanol Workshop, Engineering Foundation Conference, Henniker, N.H., U.S.A., July 8-12, 1974. Proceeding to be published.

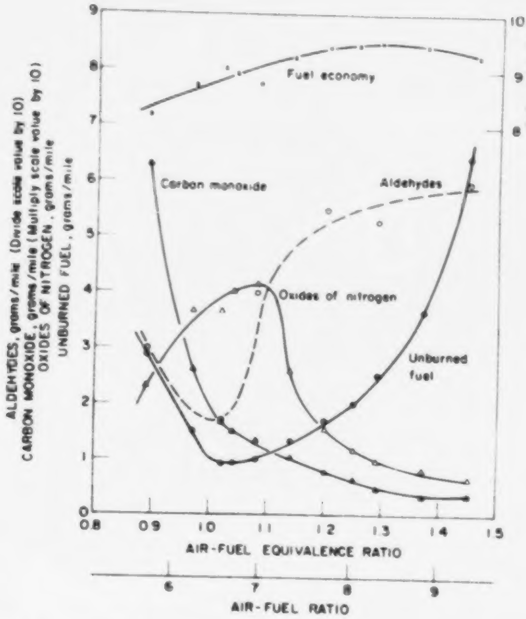

FIGURE 1.-Mixture ratio effect on methanol emissions and economy.

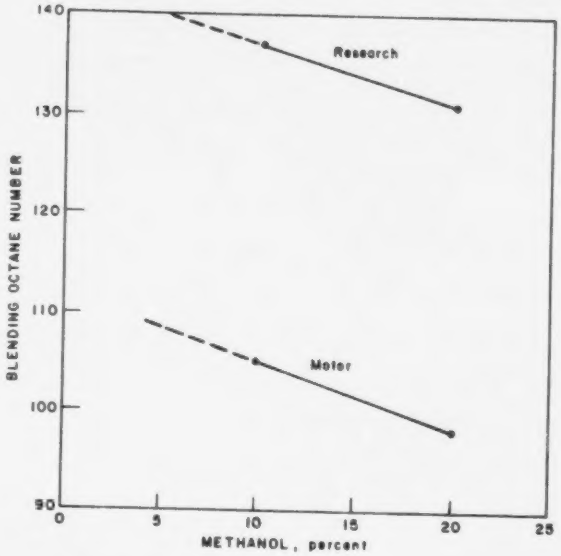

FIGURE 2.-Blending octane value of methanol.

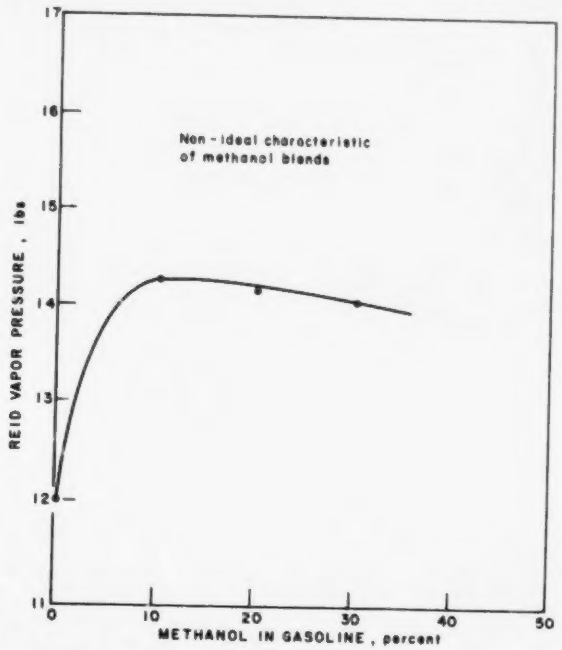

FIGURE 3.-Vapor pressure elevation with addition of methanol to gasoline.

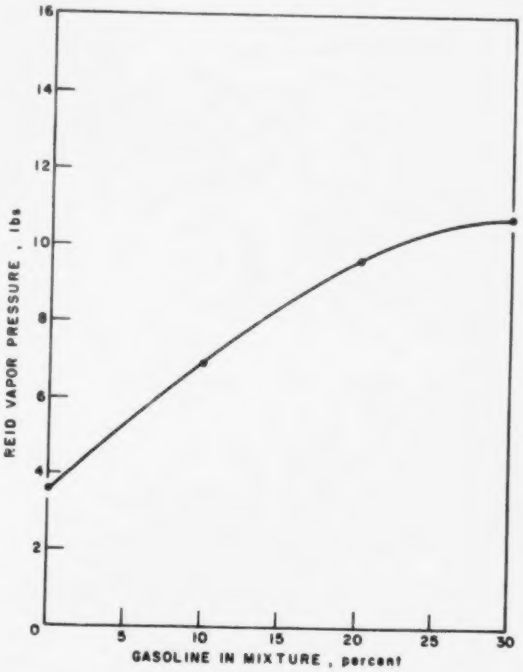

FIGURE 4.-Hydrocarbon addition to increase vapor pressure of methanol.

Vergleichende Untersuchungen von methanol- und benzinbetriebenen Kraftfahrzeugen *

H. HEITLAND, W. BERNHARDT, W. LEE
VOLKSWAGENWERK AG, WOLFSBURG

Of the possible alternative automotive fuels, methanol takes a leading place because it can, on the one hand, be produced on a non-mineral oil basis, e.g. from coal, at a comparative price and can be stored and distributed as a liquid fuel in the same way as gasoline. On the other hand, improved emission and running characteristics can be obtained with methanol. Further advantages are obtained when it is used in advanced automotive power systems. A gradual changeover from gasoline to methanol would be possible.

Parmi les carburants de remplacement possibles pour l'automobile, le méthanol occupe une place remarquable, car il n'est pas tiré des huiles minérales mais fabriqué par exemple à partir du charbon et à un prix comparable à celui de l'essence; il peut être stocké et distribué comme l'essence. D'autre part son emploi se traduit par une amélioration du fonctionnement des moteurs et par une diminution du volume des polluants. D'autres avantages sont abtenus lorsqu'il est utilisé sur des moteurs non classiques. Une utilisation progressive du méthanol au lieu de l'essence est possible.

Von den möglichen Alternativkraftstoffen für das Kraftfahrzeug nimmt Methanol einen hervorragenden Platz ein, da es einerseits auf erdölfreier Basis, z.B. aus Kohle,vergleichbar preiswert hergestellt und wie Benzin als flüssiger Kraftstoff gelagert und verteilt werden kann und andererseits mittels Methanol ein verbessertes Abgas- und Betriebsverhalten erreichbar ist. Gegenüber der Verwendung in herkömmlichen Fahrzeugmotoren lassen sich durch Einsatz in unkonventionellen Antrieben weitere Vorteile erreichen. Eine schrittweise Umstellung von Benzin auf Methanol ist möglich.

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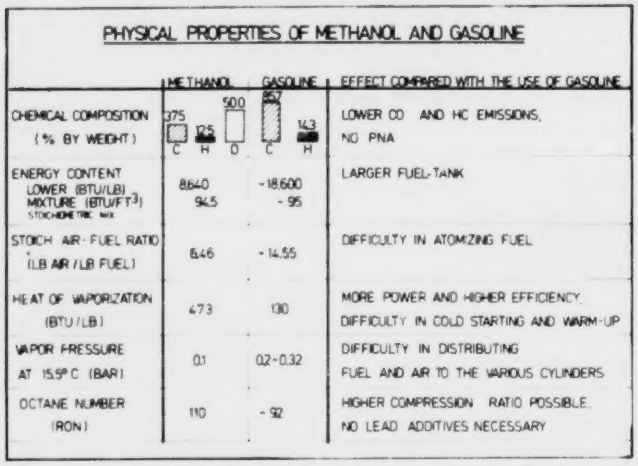
* gefördet vom Bundesminister für Forschung und Technologie

1. Eigenschaften von Methanol im Vergleich zu Benzin

Die unterschiedlichen Eigenschaften zum Benzin erfordern bei Umstellung auf Methanol zusätzliche Maßnahmen an Motor und Fahrzeug und ergeben im allgemeinen ein meist besseres Abgas- und Betriebsverhalten.



PHYSICAL PROPERTIES OF METHANOL AND GASOLINE

	METHANOL	GASOLINE	EFFECT COMPARED WITH THE USE OF GASOLINE
CHEMICAL COMPOSITION (% BY WEIGHT)	37.5 C 12.5 H 50.0 O	85.7 C 14.3 H	LOWER CO AND HC EMISSIONS, NO PNA
ENERGY CONTENT LOWER (BTU/LB) MIXTURE (BTU/FT^3) STOICHIOMETRIC MIX	 8640 94.5	 ~18,600 ~95	LARGER FUEL-TANK
STOICH AIR-FUEL RATIO (LB AIR / LB FUEL)	6.46	~14.55	DIFFICULTY IN ATOMIZING FUEL
HEAT OF VAPORIZATION (BTU / LB)	473	130	MORE POWER AND HIGHER EFFICIENCY, DIFFICULTY IN COLD STARTING AND WARM-UP
VAPOR PRESSURE AT 15.5° C (BAR)	0.1	0.2-0.32	DIFFICULTY IN DISTRIBUTING FUEL AND AIR TO THE VARIOUS CYLINDERS
OCTANE NUMBER (RON)	110	~92	HIGHER COMPRESSION RATIO POSSIBLE, NO LEAD ADDITIVES NECESSARY

Bild 1:
Unterschiedliche
Eigenschaften von
Methanol und Benzin

2. Vergleich zwischen Methanol- und Benzinbetrieb

Gemischbildung und Gemischverteilung, Kaltstart- und Warmlaufverhalten wird bei Vergasermotoren im wesentlichen durch unterschiedlichen Dampfdruck, Siedeverlauf (Bild 2) und höhere Verdampfungswärme bestimmt. Es tritt eine erhebliche Abkühlung des Luft-Kraftstoff-Gemisches bei der Kraftstoffverdampfung ein. Die starke Absenkung der Gemischtemperatur sowie der niedrige Dampfdruck führen zu Start- und Gemischbildungsschwierigkeiten, wenn nicht durch Zusatzeinrichtungen, wie z.B. intensive Vergaser- und Saugrohrbeheizung, die benötigte Wärme bereitgestellt wird, vgl. Bild 3.

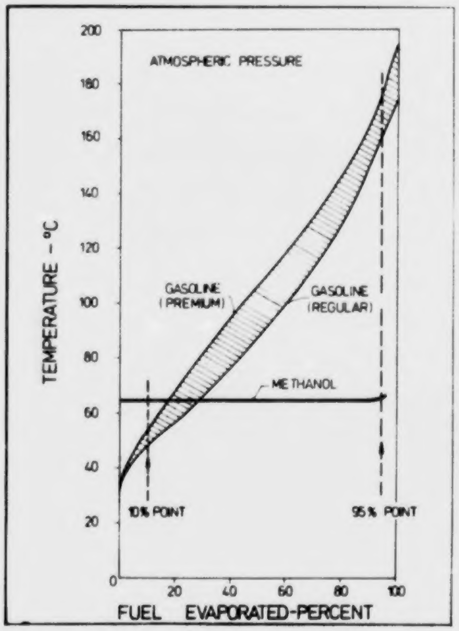


Bild 2:
Siedeverhalten von Methanol
im Vergleich zu Benzin

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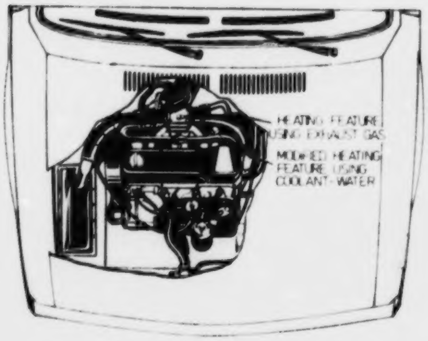

HEATING FEATURE USING EXHAUST GAS
MODIFIED HEATING FEATURE USING COOLANT-WATER

Bild 3: Umrüstung eines VW-Sciroccomotors auf Methanolbetrieb

Bei Methanol ist der auf die Masse bezogene Heizwert nur halb so groß wie beim Benzin. Deshalb müssen beim Vergaser die Kraftstoffdüsen, bei Einpritzpumpen die Fördervolumina gegenüber Benzinbetrieb vergrößert werden. Unter Berücksichtigung dieser Gegebenheiten wurden beim Volkswagenwerk einige Serienfahrzeuge, so ein VW-Scirocco (Bild 4), von Benzinbetrieb auf Methanolbetrieb umgerüstet. Eine zusätzliche Kaltstarthilfe - zentrale Einspritzung von Benzin o.ä. ins Saugrohr während des Startvorgangs sowie Austausch von methanollöslichen Kunststoffteilen, wie Schwimmer, Membrane und Dichtungen-waren notwendig. Da der gleiche Tank benutzt wurde, sank der Aktionsradius des Fahrzeugs pro Tankfüllung auf etwa die Hälfte. Mit Hilfe der Benzineinspritzung, z.B. direkt auf das Einlaßventil, konnten die Gemischbildungs- und Gemischverteilungsprobleme leichter gelöst werden, nicht jedoch die Schwierigkeiten in der Start- und Warmlaufphase, wie Versuche der Firma Daimler-Benz zeigten. Durch Zumischung leicht siedender Komponenten, wie z.B. die im Rohmethanol bereits vorhandenen höheren Alkohole oder Additive, wie Dimethyläther, Diäthyläther oder Äthylmethyläther läßt sich der Kaltstart deutlich verbessern.

Bild 4: VW-Scirocco-Methanol-Konzeptfahrzeug

Nachstehend werden einige der bei VW und Daimler-Benz erzielten Ergebnisse diskutiert. Leistung, Verbrauch und Fahrverhalten von methanolbetriebenen Fahrzeuge werden ebenfalls durch die unterschiedlichen Eigenschaften des Methanols in starkem Maße beeinflußt. Methanol und Benzin haben ungefähr gleiche Gemischheizwerte. Aufgrund der höheren Verdampfungswärme des Methanols tritt eine Abkühlung der angesaugten Luft bzw. des Methanol-Luftgemisches ein. Infolgedessen steigt der Liefergrad. Dies führt zu einer Erhöhung der effektiven Motorleistung. In Bild 5 sind die effektiven Motorleistungen des Benzin- und Methanolmotors in Abhängigkeit vom Luftverhältnis eines VW-Einzylindermotors veranschaulicht. Durchschnittlich erzielt der Methanolmotor eine um ca. 12 % höhere Leistung gegenüber dem Benzinmotor. Interessant ist, daß der Verlauf der beiden Kurven in Bild 5 ähnlich ist und die Laufgrenze der Methanolkurve sich weit in den Luftüberschußbereich hinein verschiebt. Durch Ausnutzung dieses Effektes können die Abgasemissionen im Teillastgebiet deutlich reduziert werden. Diese positiven Ergebnisse - Mehrleistung und Abgasverbesserung - konnten auch am Vollmotor, sowohl bei VW als auch bei Daimler-Benz erzielt werden.

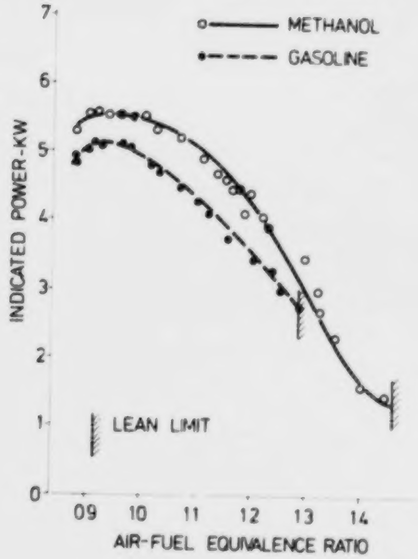
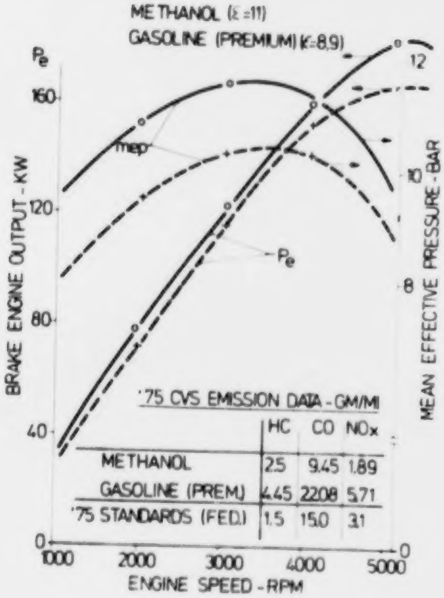


Bild 5: Effektive Leistung und Laufgrenze eines VW-Einzylindermotors bei $n = 2000\ \mathrm{min}^{-1}$ Vollast und $\varepsilon = 8{,}5$ sowie optimalem Zündzeitpunkt

Bedingt durch die hohe Klopffestigkeit des Methanols, läßt sich durch Verdichtungserhöhung gegenüber dem benzinbetriebenen Motor eine weitere Leistungssteigerung mit gleichzeitiger Verbrauchsverbesserung und günstigem Abgasverhalten erreichen, wie u. a. Versuche von DB gezeigt haben (Bild 6) Aufgrund des geringen Heizwertes des Methanols ist volumenmäßig gesehen der spezifische Verbrauch b_e des Methanolmotors verständlicherweise deutlich höher als der des Benzinmotors, aber energiemäßig gesehen, ist ein gegenüber dem Benzinmotor günstigerer Verbrauch festzustellen (Bild 7).



'75 CVS EMISSION DATA - GM/MI

	HC	CO	NOx
METHANOL	2.5	9.45	1.89
GASOLINE (PREM)	4.45	2208	5.71
'75 STANDARDS (FED)	1.5	15.0	3.1

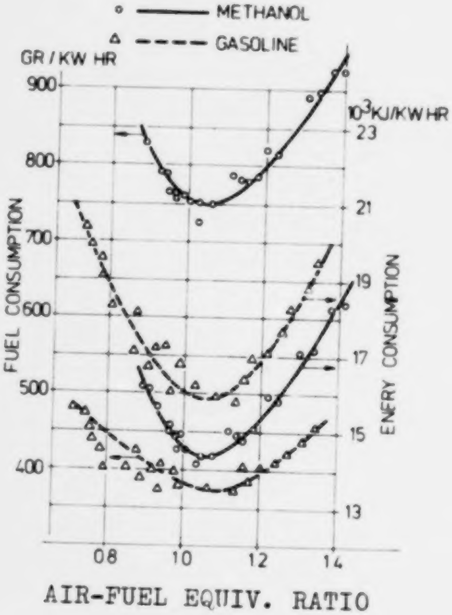


Bild 6: Leistung und Mitteldruck DB-Motor 4,5 l-V 8 bei Vollast

Bild 7: Verbrauchswerte eines VW-Einzylindermotors bei n = 2000 min^{-1}, Vollast und ε = 8,5

Diese Erhöhung des Wirkungsgrades wird durch geringere Verluste an Wandwärme erzielt. Darüber hinaus liegt die Abgastemperatur beim Methanolmotor wesentlich niedriger als die vom Benzinmotor, was auf kleinere Verluste durch die abgeführte innere Energie der Abgase schließen läßt. Bedingt durch die möglichen höheren Verdichtungsverhältnisse von methanolbetriebenen Motoren, ergeben sich mit der Steigerung des thermischen Wirkungsgrades noch weitere Kraftstoffeinsparungen, vgl. Bild 7. Abgasverhalten und Umweltaspekte lassen sich durch methanolbetriebene Motoren deutlich verbessern. Weitere Zündgebiete ermöglichen einen emissionsgünstigen Motorbetrieb mit "armen" Gemischen, die im Abgas freien Sauerstoff enthalten. Die höhere Verbrennungsgeschwindigkeit gestattet ein schnelleres Durchbrennen des Gemisches. Niedrigerer Kohlenstoffanteil im Brennstoffmolekül und auch günstigere Dissoziationseigenschaften bei mäßigen Temperaturen führen zu einer sauberen Verbrennung und damit zu neuen Brennverfahren für alternative Fahrzeugantriebe. Über die bisher vom Gesetzgeber limitierten Schadstoffe des motorischen Abgases hinaus, lassen sich lästige und möglicherweise schädliche Komponenten wie polyzyklische aromatische Kohlenwasserstoffe (PNA), Blei und Ruß nahezu vollständig vermeiden. - An einem VW Einzylindermotor wurden bei Vollast und optimaler Zündung folgende Ergebnisse erzielt:

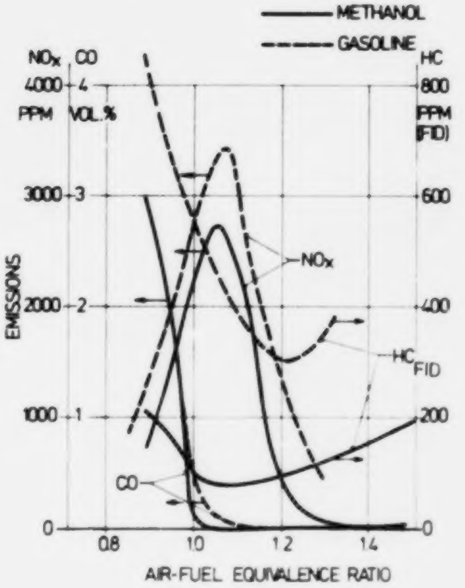


Bild 8: CO-, HC-, NO_x-Emissionen eines VW-Einzylindermotors bei n = 2000 min^{-1}, Vollast und ε = 8,5

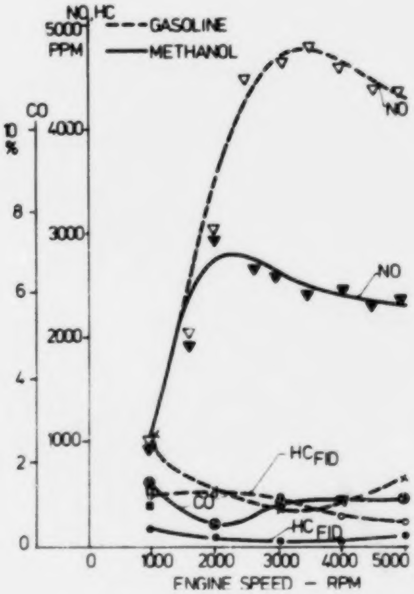


Bild 9: CO-, HC-, NO-Emissionen eines VW 1,5 l-Vollmotors bei Vollast

Die Kohlenmonoxid-Emission (CO) beim Methanolmotor entspricht in etwa der des Benzinmotors. Eine deutliche Senkung ist lediglich im Bereich λ = 1,0 bis λ = 1,1 zu erkennen, vgl.(Bild 8). Bei Untersuchungen an einem 4-Zylinder-VW-Passat-Motor unter Vollast bei verschiedenen Drehzahlen wurde festgestellt, daß eine deutliche Senkung der CO-Emission bei Methanolmotor in niedrigem Drehzahlbereich gegenüber dem Benzinmotor möglich ist, vgl. Bild 9 .Aus den in Bild 8 wiedergegebenen Kurvenverläufen der Stickoxidemissionen (NO_x) ist zu ersehen, daß beim Methanolbetrieb eine bemerkenswerte Reduktion der NO_x-Emission gegenüber dem Benzinbetrieb möglich ist. Aus den Einzylinder-Untersuchungen (Vollast, 2000 min^{-1}) ergibt sich für das stöchiometrische Luftverhältnis eine Reduktion von ca. 18 % (Bild 8), während beim Vollmotor im Bereich höherer Drehzahlen sogar eine Reduktion von ca. 50 % auftritt (Bild 9). Die wesentlich günstigere HC-Emission des Methanolmotors ist in Bild 8 und 9 deutlich zu erkennen. Berücksichtigt man ferner, daß von dieser mit dem Flammenionisationsdetektor (FID) gemessenen sehr niedrigen Konzentration eigentlich nur knapp 10 % echte Kohlenwasserstoffe sind, wie gaschromatographische Messungen gezeigt haben, dann wird deutlich, wie umweltfreundlich der Methanolmotor in Bezug auf Kohlenwasserstoffemissionen ist.

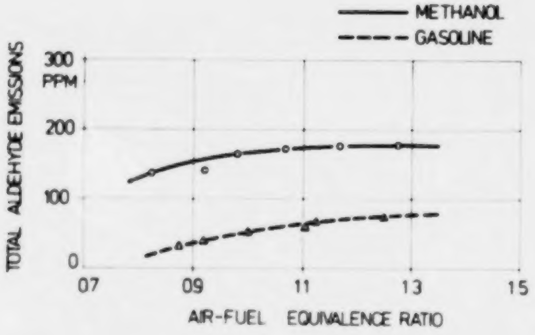


Bild 10: Aldehyd-Emission eines VW-Einzylindermotors bei n = 2000 min^{-1}, Vollast und $\varepsilon = 8{,}5$

Die Aldehydemission eines Methanolmotors ist deutlich höher als die eines Benzinmotors. Bild 10 zeigt die Emission der Gesamtaldehyde, die nach der 3-Methyl-2-Benzothiazanon-Hydrazon-Methode (MBTH) als Formaldehyd gemessen wurde. Durchschnittlich ist die Aldehyd-Emission im gesamten untersuchten Luftverhältnisbereich etwa doppelt so hoch wie die des Benzinmotors. Auch durch Verschiebung in magere Betriebszustände ist keine Verminderung der Aldehydemission zu erreichen. Möglichkeiten der Reduzierung der Aldehydemission ergeben sich durch Erhöhung des Wasseranteils im Methanol, wobei gleichzeitig NO_x weiter reduziert wird (Bild 11). Bis zu einem Wasseranteil von 10 % bleibt die HC und CO Emission praktisch unverändert. Die NO-Emission kann dabei um mehr als 50 % und die Aldehydemission um mehr als 40 % gesenkt werden. Die Einbuße der Motorleistung beträgt dabei ca. 10 %. Da der Methanolmotor gegenüber dem Benzinmotor eine Mehrleistung von mehr als 10 % aufweist, würde in diesem Falle die Leistung etwa der des Benzinmotors entsprechen. Diese Messungen wurden an einem wassergekühlten 4-Zylinder VW-Motor bei Vollast und geöffneter Drosselklappe sowie mit einer Drehzahl von 3000 min^{-1} durchgeführt. Unter Berücksichtigung des Wasseranteils betrug das Luftverhältnis $\lambda = 1{,}05$.

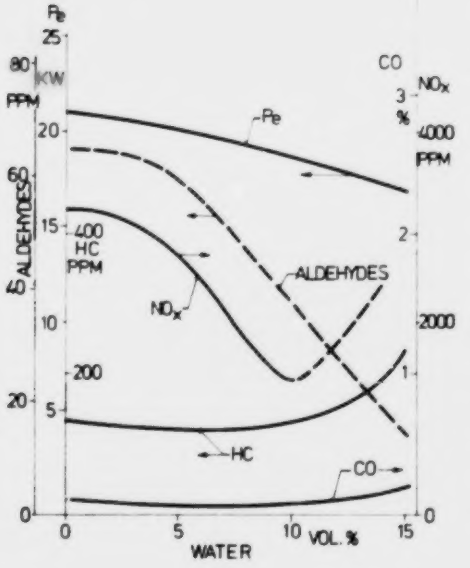


Bild 11: Reduktion der Aldehyd- und NO_x-Emission

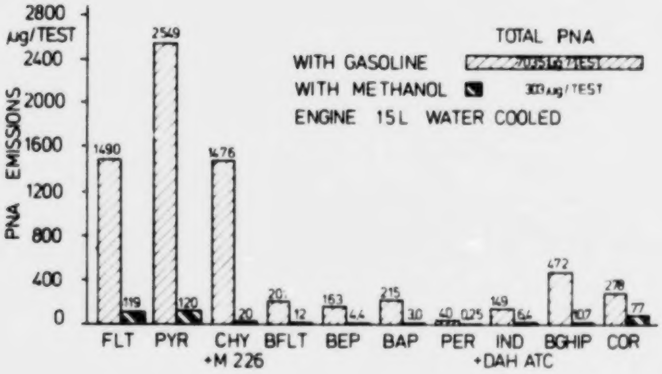


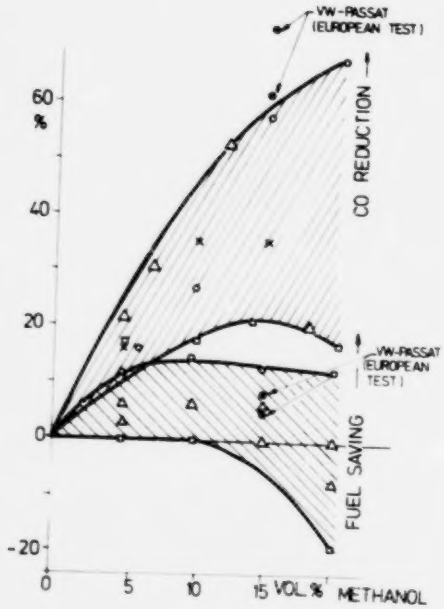
Bild 12: PNA-Emissionen eines VW 1,5-l-Motors im Europatest

Bild 12 zeigt von der VW-Forschung im Europa-Test ermittelte Absolutwerte der polyzyklischen aromatischen Kohlenwasserstoffe (PNA) (Siedebereich Fluoranthen, FLT, bis Coronen, COR) bei Methanol- und Benzinbetrieb. Die Emissionen der PNA, von denen einige als stark karzinogen angesehen werden, sind mehr als eine Größenordnung kleiner als bei Benzinbetrieb.

Insgesamt gesehen ist das Abgasverhalten eines in Ballungsgebieten mit Methanol betriebenen Fahrzeugs deutlich besser als das eines benzinbetriebenen, sowohl im Hinblick auf die bereits vom Gesetzgeber limitierten Schadstoffe HC, CO und NO_x (siehe auch Tabelle in Bild 6) als auch bezüglich weiterer kritischer Komponenten wie Schwefelverbindungen, Blei, Ruß und polyzyklische Kohlenwasserstoffe. Die höheren Aldehydkonzentrationen im Abgas methanolbetriebener Fahrzeuge lassen sich einerseits durch Wasserzugabe zum Methanol, andererseits aber auch durch vormotorische Dissoziation zu CO und H_2 vermeiden. Die toxikologischen Eigenschaften von Methanol sind dem herkömmlichen Benzin vergleichbar und dürfen gegenüber einzelnen Benzinkomponenten wie z.B. Benzol als günstiger beurteilt werden.

3. Misch-, Zweistoff- und Wechselbetrieb von Methanol und Benzin

Während der Übergangszeit bei der Einführung des Methanols als Vergaserkraftstoff werden mit Sicherheit der neue und der herkömmliche Kraftstoff parallel verwendet werden müssen. Hauptproblem beim Einsatz von Methanol-Benzingemischen ist die Frage der Entmischung durch stets vorhandene Wasseranteile. Nur 2 Bereiche sind sinnvoll, nämlich Zumischung bis zu 20 % Benzin zum Methanol und Zumischung bis zu 15 % Methanol zum Benzin. Für die Übergangszeit - geringe Mengen Methanol im Markt - ist nur die Methanolzumischung zum Benzin interessant.



Bei allen durchgeführten Versuchen ergab sich bei einer Methanolzumischung bis 10% durchweg ein Minderverbrauch. Ein VW-Passat mit 15 Vol % Methanolzumischung zum Normalbenzin, der normalerweise mit Superkraftstoff betrieben werden muß, ergab im Europa-Test einen Minderverbrauch bis 8 % gegenüber Superbenzin bei gleicher Serieneinstellung von Vergaser und Zündung. Bei allen untersuchten Fahrzeugtypen sank mit zunehmendem Methanolanteil deutlich die CO-Emission. Beim VW-Passat, der mit 15 %igen Mischkraftstoff betrieben wurde, konnte im Europa-Test eine Reduzierung der CO-Emission sogar um über 60 % erreicht werden (Bild 13).

Bild 13: CO Reduktion und Brennstoffersparnis im Mischbetrieb

Von der Firma Porsche durchgeführte CVS-Warmstarttests an einem mit 20 % Methanolzusatz betriebenem Typ 911-Fahrzeug, ergaben bei unveränderter Vergasereinstellung neben der CO-Verminderung auch bei den übrigen Schadstoffkomponenten HC und NO_x Reduktionen von 20 bis 70 %. Selbst nach erfolgter λ-Korrektur (Anreicherung auf die Ausgangswerte) verblieben noch bis zu 30 % Schadstoffverbesserung.

Weitere Vorteile der Methanolbeimischung ergeben sich dadurch, daß wegen der hohen Klopffestigkeit des Methanols der Anteil an Bleiverbindungen und an aromatischen Bestandteilen im Kraftstoff abgesenkt werden kann und daß Motortypen, die für Superbenzin ausgelegt wurden, mit einem Gemisch aus Normalbenzin und Methanol mit geringeren Kosten betrieben werden können. Nachteilig dagegen ist es, daß Maßnahmen wie Zugabe von Lösungsvermittlern, evtl. besondere Gestaltung des Fahrzeugtanks, Anbringung von wasserbindenden Filtern, möglicherweise ein zusätzlicher Tank und veränderte Pumpe beim Mischen an der Zapfsäule für den Benzin-Methanol-Mischbetrieb notwendig werden. Jedenfalls zeigten sich bei den VW-Dauerversuchen keinerlei ernsthafte Störungen an den auf Methanolmischbetrieb umgestellten Serienfahrzeugen in der bisherigen Laufzeit von 30 000 km in 9 Monaten.

Der Zweistoffbetrieb setzt getrennte Kraftstoffbehälter, Leitungssysteme und Kraftstofffördereinrichtungen voraus. Ob ein Fahrzeug ohne zusätzliche Maßnahmen alternativ oder wechselnd mit Benzin oder Benzin-Methanol-Gemisch fahren kann, muß für jeden Fahrzeugtyp getrennt nachgewiesen werden. Fahrzeuge mit guter Gemischaufbereitung und Gemischverteilung sowie serienmäßiger Ansaugluftvorwärmung tolerieren Methanolbeimischungen bis 15 Vol % ohne Änderungen an Motor und Fahrzeug. Für einen alternativen oder wechselnden Betrieb eines Verbrennungsmotors mit Benzin oder technisch reinem Methanol sind auf jeden Fall Modifikationen am Gemischbildner und am Saugrohr notwendig. Der Betrieb mit Methanol erfordert darüber hinaus zusätzliche Start- und Warmlaufhilfen. Für alle 3 Betriebsweisen, Misch-, Wechsel- und Zweistoffbetrieb, gibt es brauchbare Vorschläge, die zum großen Teil bereits im Fahrbetrieb erprobt sind.

4. Eignung von Methanol für Antriebsalternativen

Durch Einsatz von Methanol als Kraftstoff ergeben sich meist günstigere Voraussetzungen für die Entwicklung neuartiger Antriebe, mit Ausnahme von dieselähnlichen Verfahren. Versuche an Schichtladungsmotoren der Firmen Volkswagenwerk, Porsche und MAN haben gezeigt, daß Leistungssteigerungen und Wirkungsgradverbesserungen bis zu 10 %, sowie Schadstoffabsenkungen im Abgas bis zu 50 % über die schon guten Ausgangswerte hinausgehend erreichbar sind. Eine Fahrzeuggasturbine des Volkswagenwerks konnte nach Umstellung auf größeren Kraftstoffdurchsatz bei gleichbleibender Leistung mit deutlich verminderter Stickoxidemission (Absenkung auf 20 - 25 %) betrieben werden. Es darf erwartet werden, daß sich ein ebenso gutes Gesamtbild bei methanolbetriebenen Motoren sowohl mit innerer als auch mit äusserer kontinuierlicher Verbrennung ergibt. Methanol-Brennstoffzellen-Aggregate bieten in Bezug auf Leistungsgewicht und Leistungsvolumen keine wesentlichen Vorteile gegenüber anderen Brennstoffeinsätzen, sind aber wegen niedrigeren Betriebstemperaturen und Vermeidung der Rußbildung technisch leichter beherrschbar. Bedingt durch die spezifischen Eigenschaften des Methanols - leichtere Dissoziierbarkeit bei niedrigen Temperaturen und günstigeres H/C-Verhältnis gegenüber Benzin - bietet sich zur Entwicklung von Niedrigstemissionskonzepten der Einsatz im Gasgenerator an. Sowohl eine thermische als auch katalytische Spaltung ist denkbar, wobei sich insbesondere die Teilstromverfahren mit geringstem Aufwand realisieren lassen. Hier wäre auch der Einsatz geeigneter kleiner Speichersysteme zwischen Generator und Motor möglich. Bei Motoren mit innerer kontinuierlicher Verbrennung lassen sich nach Voruntersuchungen im Volkswagenwerk statt der Brennkammer vorteilhaft Druckvergaser einsetzen.

5. Wirtschaftlichkeit und Ausblick

Die Herstellungskosten für Methanol liegen nach [1] je nach Einsatzart der Primärenergie und Herstellungsverfahren zwischen 25 und 57,5o DM/Gcal, Bild 14. Sie zerfallen in die Einzelanteile wie Energie-, Kapitaldienst-, Material- und Personalkosten wobei davon der Erlös von Nebenprodukten abzuziehen ist. Es fallen zusätzliche Verteilungskosten für den deutschen Binnenmarkt zwischen 1o und 15 DM/Gcal an. Damit zu vergleichen sind stark schwankende Benzinpreise, die in Deutschland heute bei 40 DM/Gcal liegen und im März 1974 auf dem Höhepunkt der Energiekrise zu 55 DM/Gcal angegeben wurden.

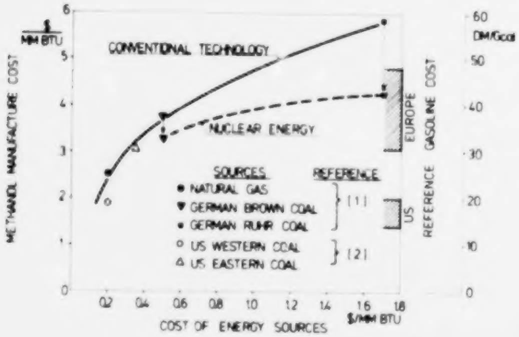


Bild 14: Methanol-Herstellungskosten mit und ohne Kernwärme in Abhängigkeit von Primärenergiekosten

(1 $/MM BTU ≈ 10 DM/Gcal)

In den USA werden Methanolpreise zwischen 1,87 und 3,o6 $/MMBTU (19 - 31 DM/Gcal) [2] genannt, vgl. auch Bild 14. Somit könnte sowohl in den USA als auch bei uns zu vergleichbaren Benzin-Wärmepreisen Methanol an den Tankstellen abgegeben werden, zumal bei Herstellung, Verteilung und Anwendung keine unüberwindbaren technischen Schwierigkeiten zu erkennen sind. Darüber hinaus bieten sich durch den zukunftsträchtigen Kraftstoff Methanol bahnbrechende Möglichkeiten für die Weiterentwicklung neuartiger Fahrzeugantriebe.

Literatur:

[1] "Neuen Kraftstoffen auf der Spur - Alternative Kraftstoffe für Kraftfahrzeuge - Teil I: Methanol", Bundesministerium für Forschung und Technologie, Bonn, Okt. 1974

[2] R. G. Jackson: "Coal-Derived Methanol as Motor Fuel", Continental Oil Company, Ponca City, Oklahoma, 1974

N. IWAI, T. TSURUGA, S. KOBAYASHI, H. SUDO

YATABE-CHO, TSUKUBA-GUN, IBARAKI 300-21 JAPAN

The combustion of methanol mixed with water was studied as an alternative fuel.

The component of NOx in exhaust gas could be reduced to the level of nearly one-tenth lower than that from gasoline engine. It was observed that the engine power was not decreased and that the formation of CO and HC gases did not increase.

As fuel supply resources, Japan must depend entirely upon imports from foreign countries. In view of the fact that the problem of dwindling oil resources has becoming a nation-wide serious problem, we take up methanol as a future fuel.

The reasons are as follows:

(1) Investigations are promoted aiming at mass-production of methanol in the near future. The reason is that from the viewpoint of transportation it will cost cheaper for Japan to import methanol by clean tankers from LNG producing countries than importing LNG by freezing tankers.

(2) There is a possibility that methanol will be manufactured in mass production in the far future by synthesizing hydrogen (H_2) with carbon monoxide (CO).

(3) Methanol can be mixed with water in free proportions and as a result, NOx in exhaust gases can be reduced.

Table 1. Properties of methanol and gasoline

	Gasoline (Octane)	Methanol
Chemical formula	C_8H_{18}	CH_3OH
Molecular weight	114	32
Specific gravity (20°C)	0.70	0.73
Air fuel ratio (stoich.)	15.1	6.45
Lower heat of combustion		
Kcal/kg	10600	4800
Kcal/l	7420	3806
(Stoich)Kcal/kg_{air}	716	78.3
(〃)Kcal/$m^3{}_{mix}$	868	841
Latent heat		
Kcal/kg	71	263
(Stoich)Kcal/kg_{mix}	4.35	35.3
Octane number (R)	100	106 (143)
(M)	100	92 (98)
Boiling point(°C)	125.7	64.7
Freezing point (°C)	-57	-97.8

Our research aims at developing a methanol fueled automotive engine which is featured to be optimum for use of methanol fuel.

In the first stage, we conducted bench tests and car tests in use of a commercial gasoline engine which was modified in part for use of both pure methanol and methanol water mixed fuel. As a result, superior factors and defects in use of these substitute fuels could be confirmed. We are now promoting studies to utilize these superior factors. We introduce here our intermediate report. We plan to develop a prototype methanol fueled automotive engine upon completing these preliminary researches.

1. Preliminary experiments by conventional gasoline engine

Firstly, bench tests were conducted in use of a commercial engine with 1,770 cc, 4 stroke-4 cylinder OHC and which was provided with an electronic fuel injection system in the intake manifold. The modification of the engine was minimized, except for a laminar flow meter which was added to the intake system and the exhaust system which was shortened and reshaped. Basic design factors were obtained through the experiments. The experiments were performed under various conditions of the engine. Such factors as excess air ratio, fraction of mixed water, ignition timing, engine speed and load were varied.

Fraction of mixed water (W/F) is defined as follows:

$$W/F = \frac{\text{Volume of water}}{\text{Volume of methanol}} \times 100\ (\%)$$

The results desclosed the following points:

Figure 1 shows,

(1) Both brake mean effective pressure (BMEP) and specific fuel consumption (BSFC) are not influenced by the effect of fraction of mixed water in rich condition. But in lean condition when fraction of mixed water increases, BMEP decreases and BSFC increases. This phenomenon is remarkable in proportion to an increase in lean conditions.

Figure 2 shows,

(2) When fraction of mixed water increases, CO-emission decreases in rich condition.

(3) When fraction of mixed water increases, HC (almost unburned methanol) emission increases

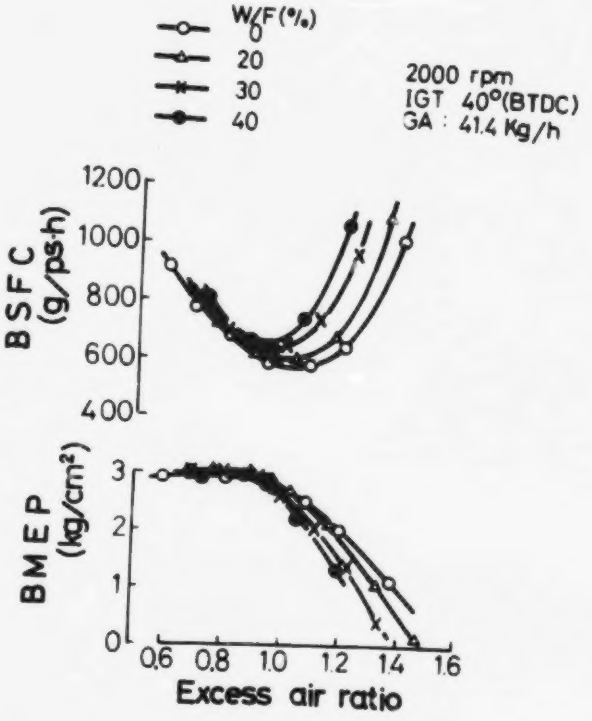


Figure 1. Engine performance

in all conditions. When lean condition, especially, excess air ratio exceeds 1.2, this phenomenon is remarkable.

(4) When fraction of mixed water is increased, NOx-emission decreases remarkably. However, fraction of mixed water is increased more than 30%, reduction of NOx emission may not be expected sufficiently.

(5) Figure 3 shows that, when power output is reduced by 10% through letting ignition timing retarded, NOx emission decreases by nealy 70%.

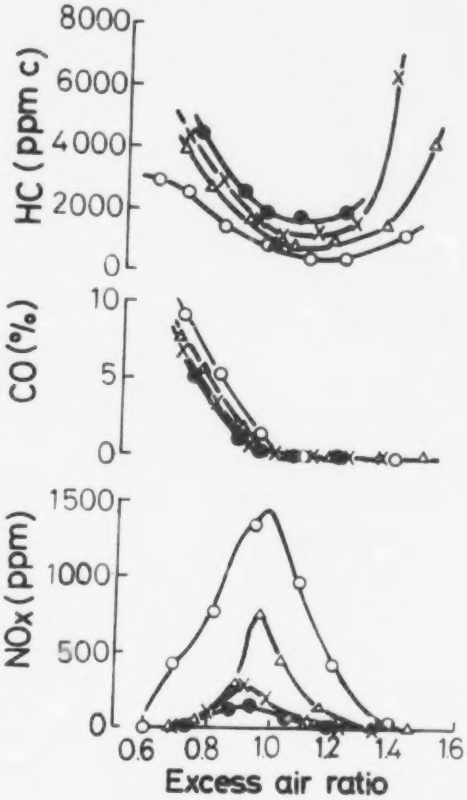


Figure 2. Emission

After these various factors were studied, the following design parameters were decided on:

(a) The ratio for mixing methanol with water will be 0.3 vol. (W/F = 30%) of water for 1 vol. of methanol.
(b) Air excess ratio will be 1.1.
(c) Ignition timing will be set at a point allowing 90% of the maximum power timing.
(d) Idling will be allowed at a point of ignition timing of 20° (B.T.D.C.)

In order to meet these requirements, the electronic fuel injection equipment was modified so that air excess ratio could be kept at 1.1 under water mixing ratio of 30%. In addition, the setting of spark advance was changed so that 90% of maximum power could be obtained. The engine, modified in these ways, was mounted in a passenger vehicle weighing approximately one ton. It is noted that methanol fuel is qualitatively inferior in its greater latent heat of vaporization which deteriorats the starting performance of engines. In order to resolve this trouble, and additional fuel supply

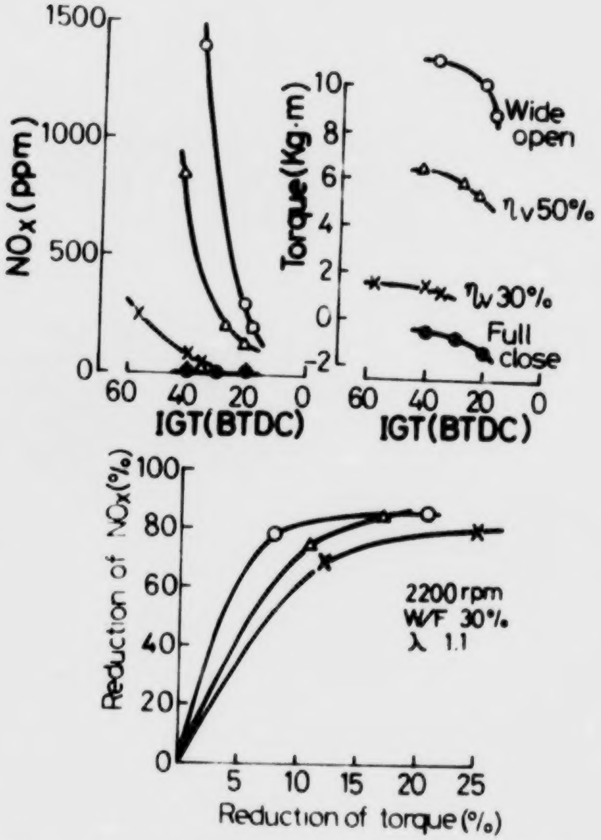


Figure 3. Effect of ignition timing

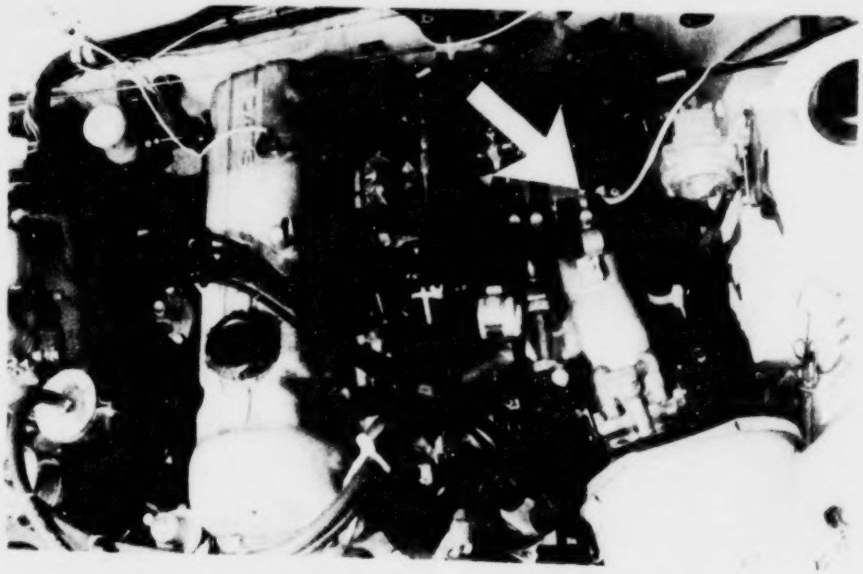


Figure 4. Gasoline injection nozzle specially equiped at the position of ⇘

Table 2. Results of mode tests

MODE	10 MODE (g/km)						LA-4 (g/mile)			Cat.temp(℃)	
Cat.	Without cat.			With cat.			With cat.			(10 MODE)	
(km)	HC	CO	NO_x	HC	CO	NO_x	HC	CO	NO_x	Inlet	Outlet
100	8.17	13.69	0.19	0.21	0.87	0.17					
3000				0.45	0.19	0.15	0.55	0.48	0.25	220	400
Target	0.25	2.1	0.25	0.25	2.1	0.25	0.41	3.4	0.4		

HOT START

system was added which feed gasoline when starting the engine. In addition, a PT catalyzer equipment was provided in the position of submuffler and also a secondary air pump was attached to the engine in aid of removing CO and HC gases.

Table 2 shows results of mode tests.

Since it is difficult to obtain favorable performance for acceleration during unwarmed condition of the engine, the tests were conducted under the condition of hot start of the engine.

Table 3 shows results of acceleration performance tests.

Table 3. Results of acceleration performance tests

Accelerating performances

		Km/h	sec
passing	3rd	30 → 80	15.9
		40 → 80	12.5
	4th	40 → 80	17.5
		40 → 100	27.9
starting	0 → 400 m		22.6

Max. speed

Max. speed	150 Km/h

This figure was not excellent as compared with that of gasoline engine vehicle.

Figure 5 shows results of fuel consumption tests.

Although its fuel consumption rate is not excellent as compared with the gasoline engine, its thermal efficiency will be equal, because heat of combustion of methanol was about half of gasoline. The engine was disassembled and inspected after an endurance test of 10,000 kilometers. There could be found no particular troubles in the inspection.

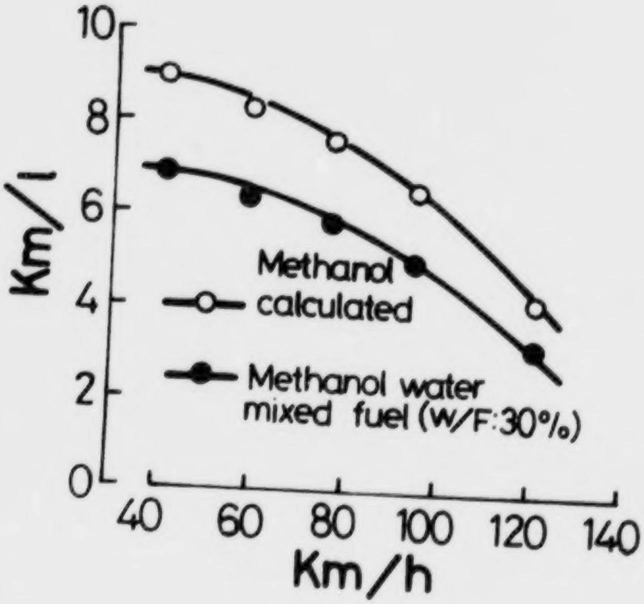


Figure 5. Results of fuel consumption tests

The characteristic points are shown as follows:

(1) There will be less accumulation of carbon deposit is in the combustion chamber and in the exhaust system. (Figure 6a, 6b, and 7)
(2) There will be some water to be contained in lubricating oil. (Figure 8)
(3) Corrosion of piston is observed to some extends. (Figure 6b) But corrosion at the fuel system will be negligible. (Figure 9)

Then, we consider characteristics of methanol for fuel from this preliminary experiments. So the results disclosed the following points:

Questionable points;

(1) Methanol is inferior in the starting and accelerating performance of engines. It is apt to be exhausted as unburned methanol. The reason is that vaporization and mixture formation are insufficient because of the large vaporizing latent heats of methanol and water.
(2) Further studies are necessary on the problem of corrosion.
(3) Deterioration of lubricating oil should be studied still further.
(4) Removing of formaldehyde in exhaust gas should be studied (it can be removed) by using a thermal reactor with catalitic convertor.
(5) Fuel consumption will increase, because the heat of combustion is inferior.

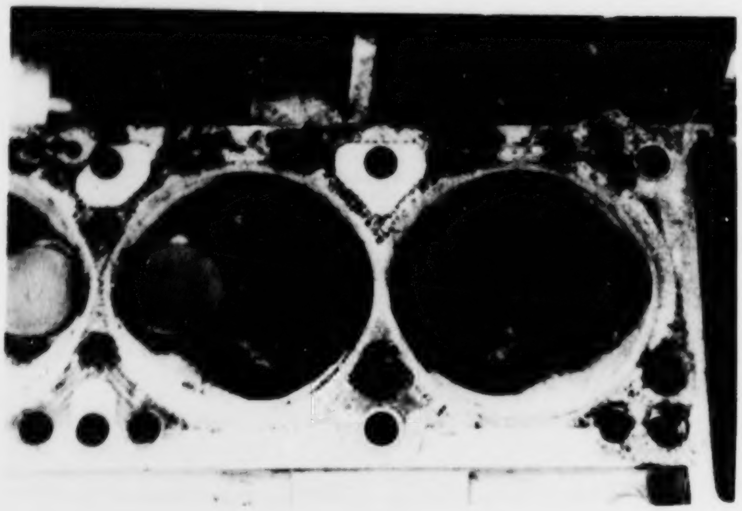


Figure 6a. Carbon deposit in the combustion chamber

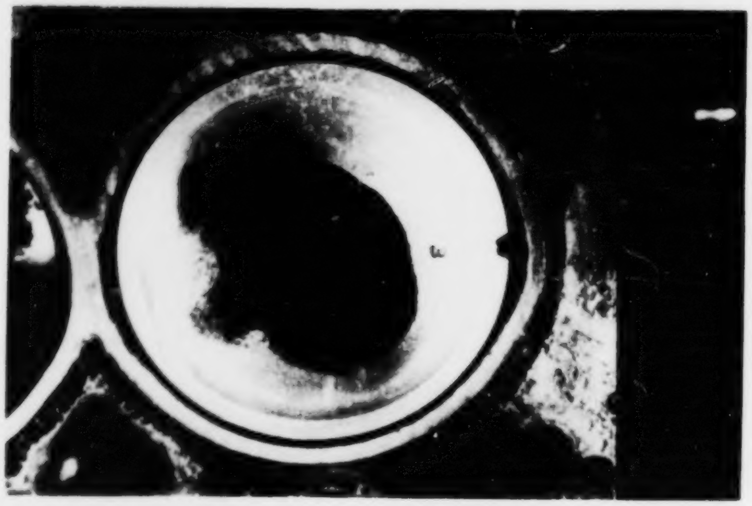


Figure 6b. Carbon deposit on the piston

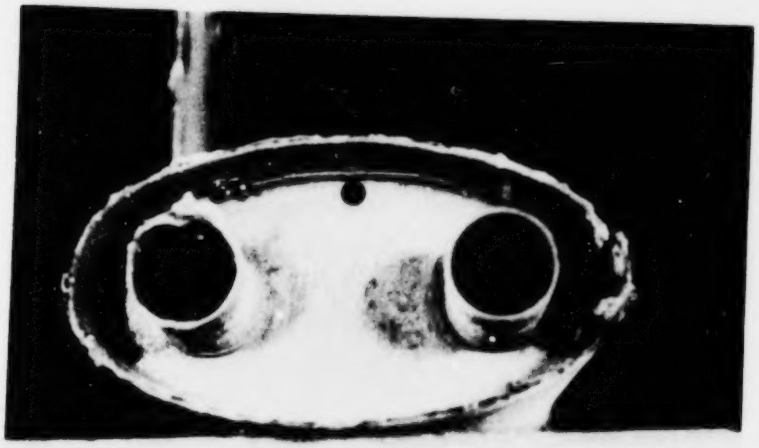


Figure 7. Carbon deposit in the exhaust system

Figure 8. Water in lubricating oil

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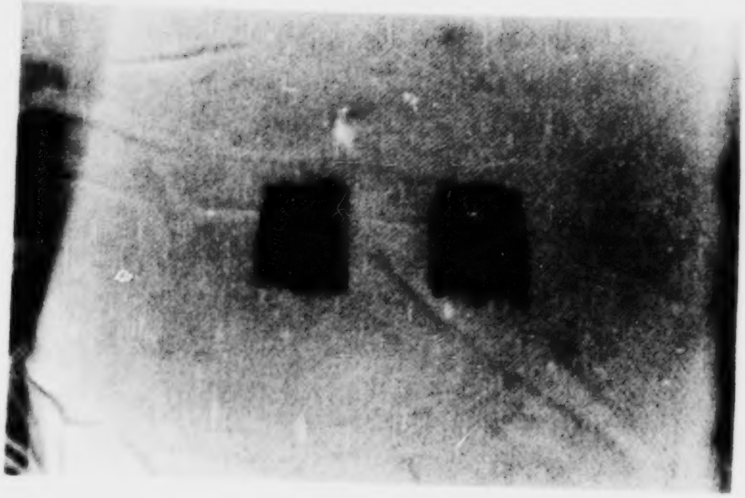

Figure 9. Corrosion of the fuel system

Excellent points;

(1) Compression ratio can be increased since methanol has a high octan number.

(2) Since the volume of fuel to be supplied every unit cycle is large, minute metering for direct fuel injection into combustion chamber can be improved. In addition, fuel injection nozzle is kept free from stopped up, because there is neither soot nor tar as the combustion products of methanol.

(3) The wall of combustion chamber is kept clean, because there is no soot producted from methanol combustion.

2. The preliminary tests needed for development of a prototype methanol engine

Through the above-mentioned preliminary tests which were conducted with gasoline engines, we confirmed the possibility that methanol can be used as an automobile fuel. We must consider sufficiently both superior and inferior factors as mentioned above in order to make a prototype methanol engine in a real sense. For example, we must inquire still further into such subjects as vaporization, mixture formation of methanol and water, optimum compression ratio, possibility of direct fuel injection into the combustion chamber and optimum shape of combustion chamber. We are now pushing forwards these researches. In this report

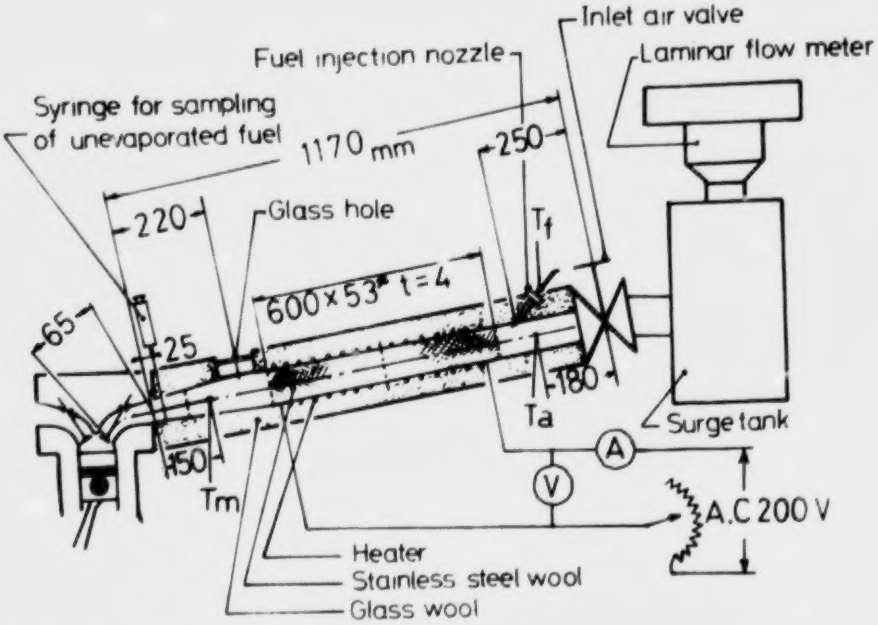

Figure 10. Schematic view of the experiment

we describe the effect of vaporization.

2-1. Effect of vaporization

A test was conduced in use of an engine of 322.3 cc with 4 strokes and single cylinder OHC. By heating its intake manifold its engine performance and exhaust emission, which affected by fraction of evaporated fuel and temperature of mixture, were investigated. In order to control the mixture temperature in the intake pipe, the electric heater was used.

Figure 10 shows a schematic view of the experimental systems.

Calculation method for vaporization rate

Evaporation rate was calculated as follows:

In the case of pure methanol or gasoline

$$Q_e = G_a \cdot C_{pa}(T_m - T_a) + G_f \cdot C_{pf}(T_m - T_f) + G_f \cdot x \cdot H_{Lf}$$

$$x = \frac{Q_e - G_a \cdot C_{pa}(T_m - T_a) - G_f \cdot C_{pf}(T_m - T_f)}{G_f \cdot H_{Lf}}$$

where

Q_e : Calories obtained by electric heat (cal/sec)

G_a : Quantity of inlet air (g/s)

G_f : Quantity of methanol or water (g/s)

C_{pa} : Specific heat of air at constant pressure

C_{pf} : Specific heat of air or water at constant pressure

T_a : Inlet air temperature in front of heater

T_f : Fuel temperature in front of heater

T_m : Mixture temperature through the heater

H_{Lf} : Latent heat of methanol or gasoline

x : Fraction of methanol evaporated

In the case of methanol - water mixed fuel

$$Q_e = G_a \cdot C_{pa}(T_m - T_a) + G_f \cdot C_{pf}(T_m - T_f) + G_f \cdot x \cdot H_{Lf}$$
$$+ G_w \cdot C_{pw}(T_m - T_f) + G_w \cdot y \cdot H_{Lw}$$

$$z = (1-x) \cdot G_f / (1-y) G_w$$

where

G_w : Mass of water (g/s)

C_{pw} : Specific heat of water at constant pressure

H_{Lw} : Latent heat of water (cal/g)

z : Mass ratio of methanol to water by measured gas-chromatograph

y : Fraction of water evaporated

and ΔQ is given for latent heat of unevaporated fuel. U is given as latent heat of evaporated fuel divided by total latent heat of supplied fuel.

$$\Delta Q = (1-x) \cdot G_f \cdot H_{Lf} + (1-y) G_w \cdot H_{Lw}$$

$$U = \frac{x \cdot G_f \cdot H_{Lf} + y \cdot G_w \cdot H_{Lw}}{G_f \cdot H_{Lf} + G_w \cdot H_{Lw}}$$

The results disclosed the following points:

Figure 11 shows,

(1) Lowering of mixture temperature leads to a decrease in vaporization rate. This trend is shown clearly if the fuel contains a greater portion of water.

(2) The engine power (thermal efficiency) decreases when

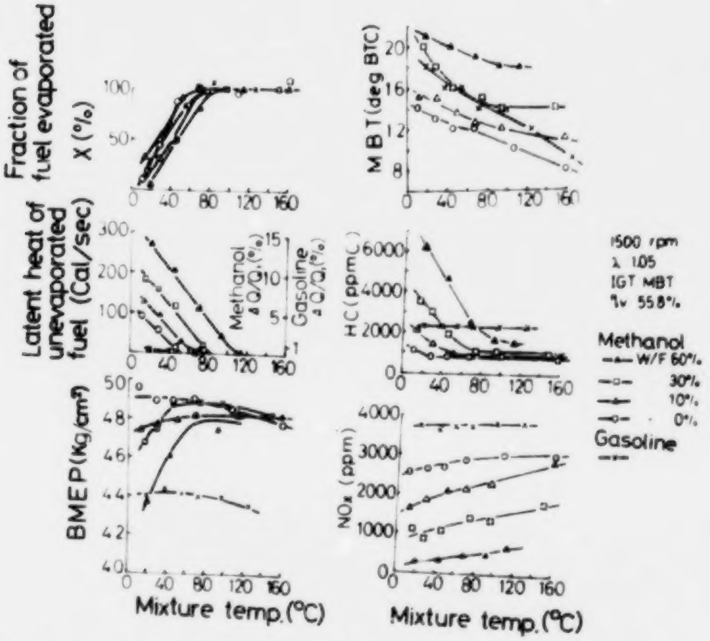

Figure 11. Fraction of fuel evaporated, engine performance, and emission

the temperature of mixture is low and rate of mixed water is high.

(3) The maximum power timing advances following the lowering of mixture temperature.

(4) HC component increases suddenly following a decrease of mixture temperature, when the fuel contains a greater portion of water.

Figure 12 shows,

(5) HC component increases and the power decreases begining from the point where the heat of vaporization of unvaporized fuel reaches nearly 5% of the total combustion heat.

Figure 13 shows,

(6) When vaporization rate is varied, increases of latent heat of unvaporized fuel nearly coincide with decreases of the heat loss of cooling water. It is assumed, therefore, that almost the unvaporized fuel vaporizes by the heat of intake air port, intake valves and the combustion chamber wall after sticked to these portions.

(7) When the intake pipe is heated, there would be observed no marked increases in HC emission, even if the rate of mixed water is increased. However, the Figure 14 shows that the power decreases as the volume of intaked air decreases due to the expansion of fuel air

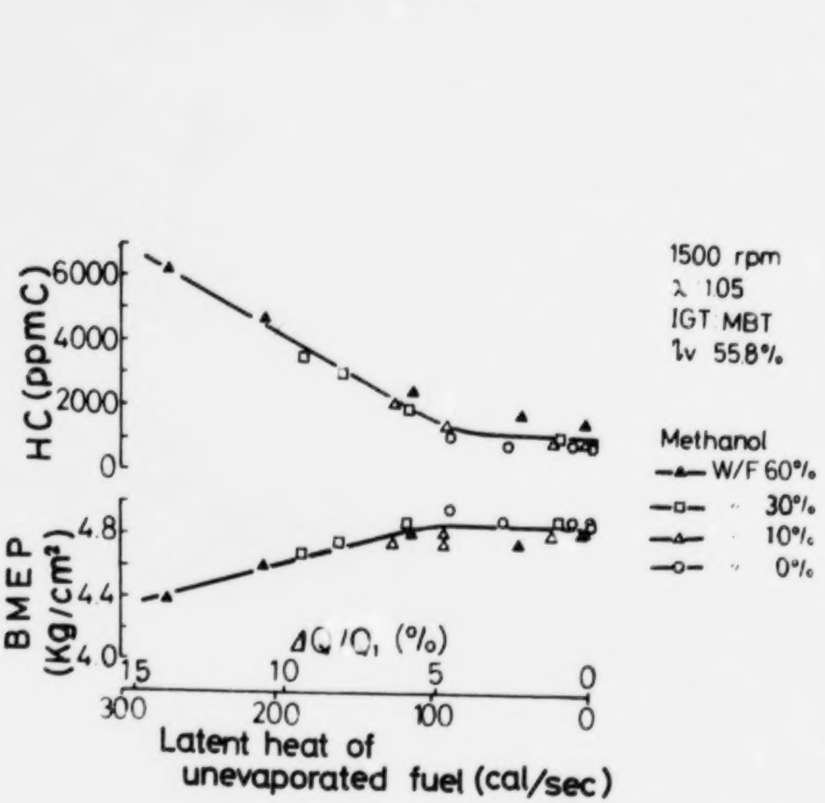

Figure 12. Effect of latent heat of unvaporized fuel

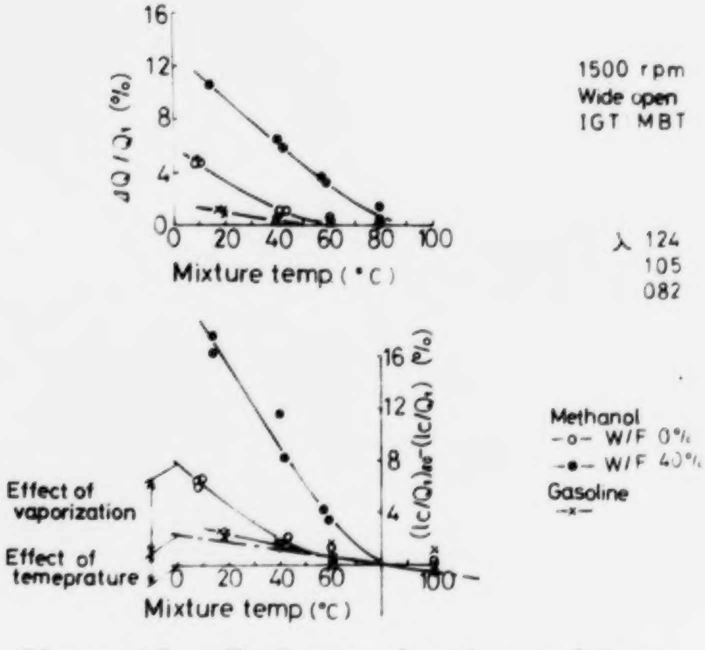

Figure 13. Fuel vaporization and heat loss of cooling water

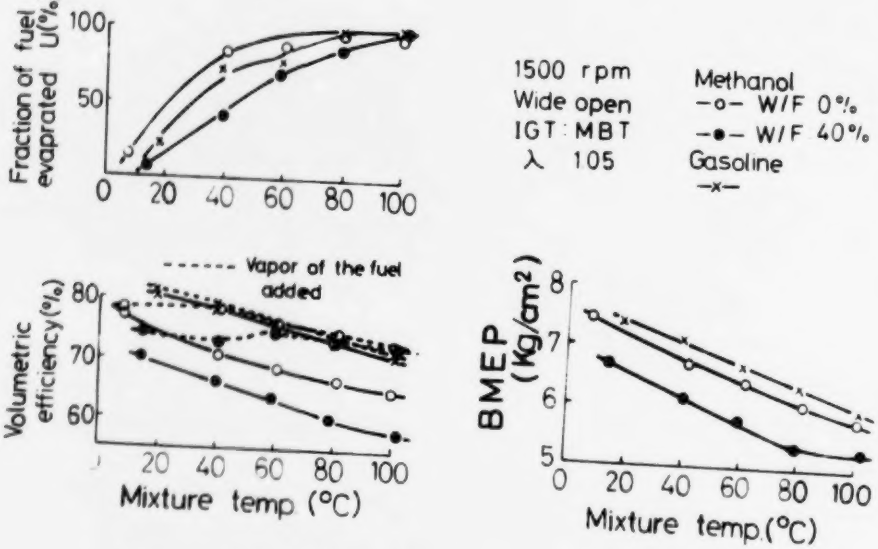

Figure 14. Maximum power

mixture.

Mentioned above is the effects of mixture temperature and vaporization rate of methanol to be exerted upon the various performances relating to engines and emissions. We are going to inquire still further into a heating system, that is heat exchangers for practical use.

3. Conclusion

We report here the result of methanol fuel experiments which have been conducted in use of a conventional engine originally designed and manufactured for use of gasoline. In addition, we plan to design and make a prototype methanol engine for automobile taking various excellent properties of methanol into full consideration.

The authors wish to gratefully acknowledge Prof. Dr. Osamu HIRAO of University of Tokyo's Institute of Industrial Science and Mr. Yukio MIYAMORI, Director of Emission Research Department, Nissan Motor Company for instruction and assistance in our research.

FUTURE ROLES FOR HYDROGEN FUEL IN SURFACE TRANSPORTATION SYSTEM APPLICATIONS

WILLIAM J. D. ESCHER
Escher Technology Associates
St. Johns, Michigan 48879
U. S. A.

Surface transportation systems ultimately must derive their mode of energy from non-fossil energy sources: nuclear, solar, geothermal. To this end, Hydrogen Energy, like electricity, is a candidate "energy carrier," offering improved transportability and storability. While hydrogen poses distinct engineering challenges, it is demonstrably an excellent fuel, intrinsically providing for both maximum vehicular energy conversion efficiency plus minimal polluting emissions.

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Need for Non-petroleum and, Eventually, Non-fossil Alternative Fuels

Sensitized by the recent events surrounding oil supplies of the past year, it is especially clear to us that petroleum-based fuels are critically fundamental to the operation of our present-day world transportation system: surface, air, and marine. Indeed, in 1972 the U.S. National Petroleum Council in its report on "The United States Energy Outlook"(Reference 1) underscored the fact that domestic oil-based fuels would likely be in increasing short supply unless extraordinary measures were taken. The NPC recommended accelerated development of the nation's coal and nuclear resources, specifically for the fast-growing electricity market. This would provide an effective means of shifting end-use energy consumption over to non-petroleum resources, reducing dependence on domestic and imported oil and natural gas which are in increasingly short supply as events have borne out. Hopefully, by this strategy, sufficient petroleum based fuels would then be available for those sectors uniquely dependent on them, transportation being far and away the largest of these.

The obvious complementary, but later-timed strategy would be the direct production of alternative fuels from non-petroleum sources: coal, oil shale, tar sands and, eventually perhaps, direct fuel synthesis from non-fossil sources. Further, in the case of prospective U.S. planning, to limit the escalating otherwise mandatory requirement for oil importation, emphasis would be on the development of domestic unconventional sources for non-petroleum based fuels.

As illuminated in recent preliminary assessments of this strategy by Exxon Research and Engineering Company (Reference 2) and the Institute of Gas Technology (Reference 3) supported by the Alternative Automotive Power Systems Division of the U.S. Environmental Protection Agency, the conclusion is that the potential domestic resources which can be developed effectively by the end of this century reduce to coal and oil shale. A companion paper at this Conference summarizes these studies (Reference 4).

Numerous activities connected with the future development of non-petroleum based alternative fuels, whcih include gasoline and distillate type fuels, and methanol (alone or as an additive to gasoline) are now getting underway in the United States and in other nations of the world. An example is the Federal leasing of oil shale bearing lands in Western Colorado for demonstration programs by the oil producing and processing industry. More limited planning is also underway on longer range possibilities including the utilization of non-fossil energy resources for the production of alternative fuels. It is this longer range viewing of the transportation energy situation which the present paper is attempting to address.

In the long run it is quite evident that even if coal and oil shale can be successfully used for the production of alternative fuels in large scale, as in the case of petroleum and natural gas today, these fossil resources will also become exhausted as far as economically feasible availability. A number of studies have been devoted to attempting to determine the magnitudes, and perhaps more pressing, the timing for such a "fossil fuel exhaustion" situation. Based on the various domestic and world demand/supply models which have examined in this, a wide-range spread of results have been developed with litreal concensus among the experts in energy projections. There is, however, little question of the ultimate necessity for evolving into a non-fossil energy system at some point in time if we are to continue to support world energy demand.

It is with respect to this long term view that the present paper is tendered. Because (1) there is uncertainty in the ultimate "need date", and (2) the development lead times are undoubtedly very long (and equally uncertain), it is prudent for today's planning activity to encompass this ultimate situation. Hydrogen produced from water by means of non-fossil primary energy sources such as nuclear and solar offers one alternative means of sustaining world energy demands into the post-fossil age which is approaching, however dimly perceived from the vantage point of today. Specifically, it is proposed that transportation fuel needs can eventually be entirely met through the use of "hydrogen-energy", a prospect we will be further examining in the paper.

Returning to the issue of the inevitability of world fossil fuel exhaustion, and assessments to date of the magnitudes and timing, Figure 1 reflects a typical finding of Elliott and Turner in their 1972 study, "Estimating the Future Rate of Production of the World's Fossil Fuels." This particular presentation is based on the largest of three "bracketing" estimates of world ultimate fossil fuel resources, viz. 238 x 10^{21} J. What is reflected is projected trends created by world demand (ascending portion of the curve from left to right) and remaining supply (descending part of the curve) leading to the characteristic bell-shaped cures. The area under the curves represents the total resource.

In Figure 1 the middle curve noted as "fluid fossil fuels" refers to petroleum and natural gas. This assumes no conversion of coal -- which is far more plentiful as evidenced by the upper curve -- to "fluid fuels", e.g. substitute natural gas, SNG. Note that world maximum production is reached at the end of the first decade of the next century, only 40 years or so from now. If coal is gasified and/or liquefied a substantial augmentation in total energy produced occurs (upper curve). But the significant thing to note is the brief postponement of only about one decade of the time of maximum production.

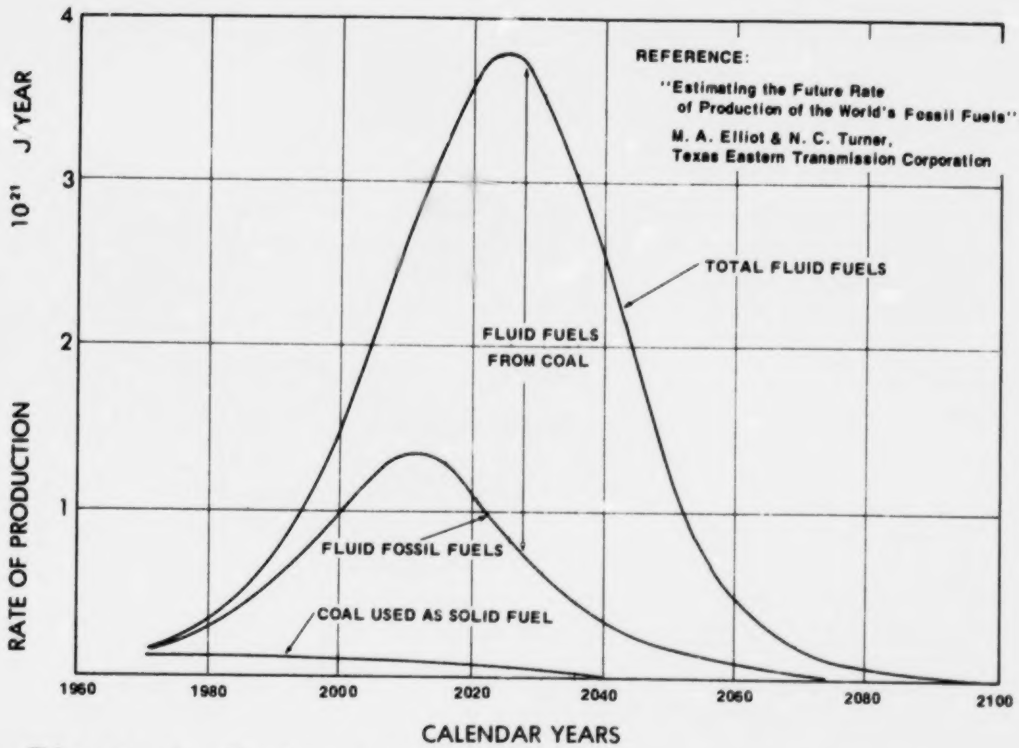

Figure 1 - Projected Rate of Production of World Fossil Fuels

It should be definitely pointed out that the Elliott and Turner study assumes no substantial use of nuclear or other non-fossil energy resources during the period in question. Indeed, the basic conclusion of the analysis is that such non-fossil resources must be developed for large scale energy production, and with a sense of urgency. Because of the long developmental and construction lead times and the very large capital investments involved, it already may be "late in the day" in view of the fact that only nuclear-electric plants are presently being deployed in the non-fossil energy category. Unfortunately, these have not been without problems the sum total of which have slowed down the previously projected build-up of capacity.

Further, germaine to the issue being addressed, electricity may play a very limited role in supplying transportation systems with energy since traditionally transportation has depended on portable chemical fuels.

The Hydrogen-Energy System Concept

In the previous section, we have addressed as a "given" the fact that the world's energy demand must be eventually supported via non-fossil energy resources. Practically, these narrow down to nuclear, solar and geothermal sources.

With the possible exceptions of nuclear-powered ships, a concept which has been technically demonstrated, and nuclear-powered aircraft (an idea which has been seriously advocated), none of these ultimate energy sources are directly amenable to operating transportation systems. This is especially true of surface transportation with its very large number of small individual elements, e.g. trains, buses, except for the obvious case of electrified rail systems which could readily be operated on nuclear-electricity, say. With the development of of advanced storage battery systems -- prospects for which are being discussed at this meeting -- nuclear or solar electricity could be harnessed, conceivably, by the private automobile in the future.

Observing that, in view of developmental uncertainties and the limitations intrinsic to system electrification, it may be necessary to provide for other options for linking transportation to non-fossil primary energy sources, the possibility of developing a non-fossil based alternative fuel is certainly worthy of our attention as planners. One such candidate fuel is hydrogen, or more generally, "hydrogen-energy" which is a term used to embrace, not only hydrogen alone for use in airbreathing devices, but the unique hydrogen-oxygen bireactant combination resulting from the water-splitting reaction to be associated with non-fossil primary energy sources of the future.

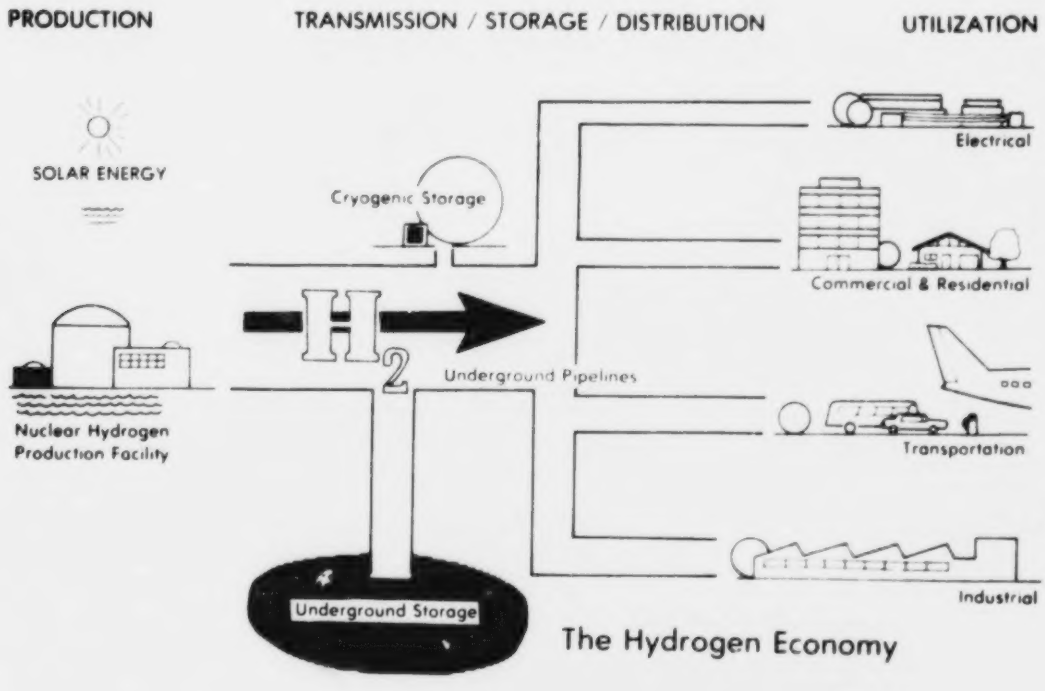

Figure 2 - The Hydrogen-Energy System Concept

Advanced thinkers in the energy field in a number of nations of the world are considering a general hydrogen-energy system concept, sometimes referred to as "The Hydrogen Economy" (as an alternative view vis-a-vis the "All Electric Economy" espoused in other corners. Figure 2 schematizes this concept. Note that transportation is represented as a principal utilization sector.

The scope of this paper does not permit a further discussion of the concept but the elements should be self-expalnatory from the figure. A considerable number of technical references on hydrogen-energy have been developed such as the definitive assessment by the Institute of Gas Technology (Reference 5) and the U.S. Synthetic Fuels Panel of 1972 (Reference 6).

Numerous technical sessions of the U.S. Intersociety Energy Conversion Engineering Conference (IECEC) have been devoted to hydrogen-energy subjects and at least one international conference, the THEME Conference held in Miami in March 1974, was devoted wholly to this subject (Reference 7).

Production, Delivery and Safety Aspects of Hydrogen for Transportation Usage

In the context of such a general hydrogen-energy system, what will comprise the hydrogen production delivery system for surface transportation systems? Figure 3 provides a functional diagram example of how this might be mechanized in the case of nuclear-electrolytic production, high pressure gas pipeline transmission and liquid hydrogen fueling of vehicles from "service stations." As will be illustrated, automotive vehicles have been already demonstrated operating on hydrogen fuel, in some cases using cryogenic liquid hydrogen (cryohydrogen).

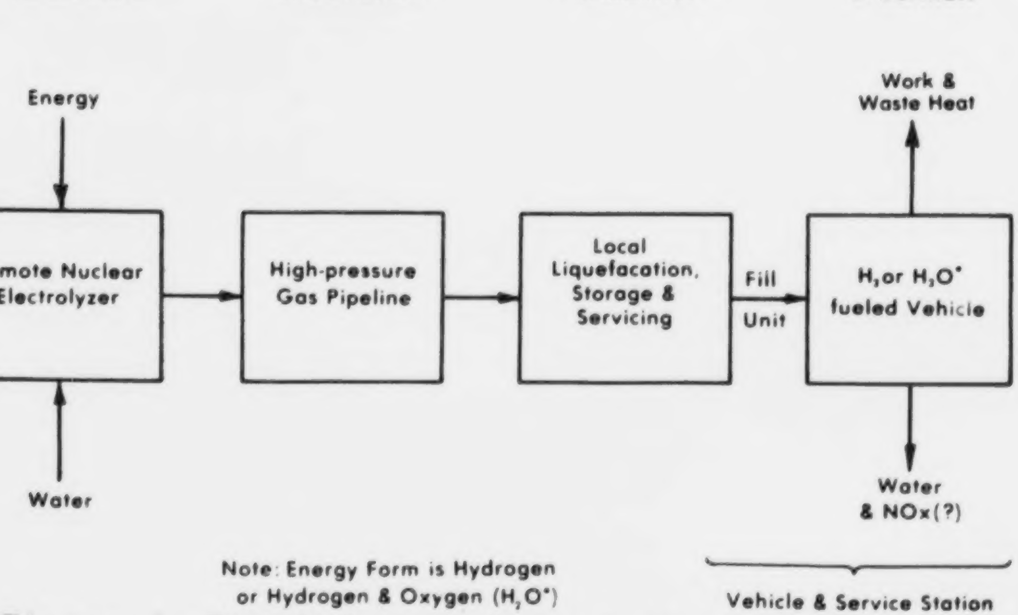
PRODUCTION
TRANSMISSION
DISTRIBUTION
UTILIZATION
Energy
Work & Waste Heat
Remote Nuclear Electrolyzer
High-pressure Gas Pipeline
Local Liquefaction, Storage & Servicing
Fill Unit
H_2 or H_2O^* fueled Vehicle
Water
Water & NOx(?)
Note: Energy Form is Hydrogen or Hydrogen & Oxygen (H_2O^*)
Vehicle & Service Station

Figure 3 - Example Hydrogen-Energy System

An alternative "scenario" to that reflected in Figure 3 which has been proposed is the solar production of cryogenic hydrogen and oxygen in large floating mid-ocean based facilities, with delivery of cryogenic hydrogen-energy to global ports in "cryo-supertankers". In this case cryogenic transmission via insulated pipelines might be used to distribute the energy-form to service stations for use in vehicles. There are numerous other options, obviously.

A word about the safety aspects of hydrogen is appropriate. Like any fuel, hydrogen can be dangerous. Accidents and incidents involving hydrogen conflagrations have been documented as with other fuels (e. g. Reference 8). With hydrogen, there seems to be considerable difficulty in sorting out the "emotional" issues from the strictly technical ones (the so called "Hindenburg Syndrome"!). But if perspective be maintained, experience has well demonstrated that hydrogen (and oxygen) can be safely handled in all facets of production, delivery and end-use provided properly trained and equipped personnel are involved.

Perhaps the most impressive testimony in support of this statement is the accomplishment of the objectives of the U.S. manned lunar program, which was predicated to a large extent on the use of hydrogen-energy. Cryogenic and gaseous hydrogen and oxygen were utilized for rocket propellants and for fuel cell operation to supply spacecraft electrical power for the voyage to the moon and back. This is especially noteworthy if it is noted that hydrogen-energy as a serious technological ingredient of the space program was introduced no earlier than the early 1960's.

With regard to the technical characteristics of hydrogen for use in transportation systems, the limited scope of the present paper prevents a substantive coverage of this other than the several summary points to be included in the "Concluding Observations" at the end. The author's reports on this subject (References 9 - 10) and other publications in the field can be referred to for this background.

The fact that, at least on a demonstration basis, hydrogen can be utilized in conventional transportation systems is evidenced in Figure 4. These photographs show a standard U.S. Postal Service Jeep utility vehicle which has been modified to operate with cryogenic liquid hydrogen fueling. The modification program was carried out by graduate students at the University of California, Los Angeles (UCLA) under a research contract from the U.S. Department of Transportation. The vehicle was donated by the U.S. Postal Service.

The engine modification (Figure 4, lower) incorporates a water induction system to suppress manifold backflashing and to reduce oxides of nitrogen production. The vehicle has a range of about 400 miles on its installed tankage.

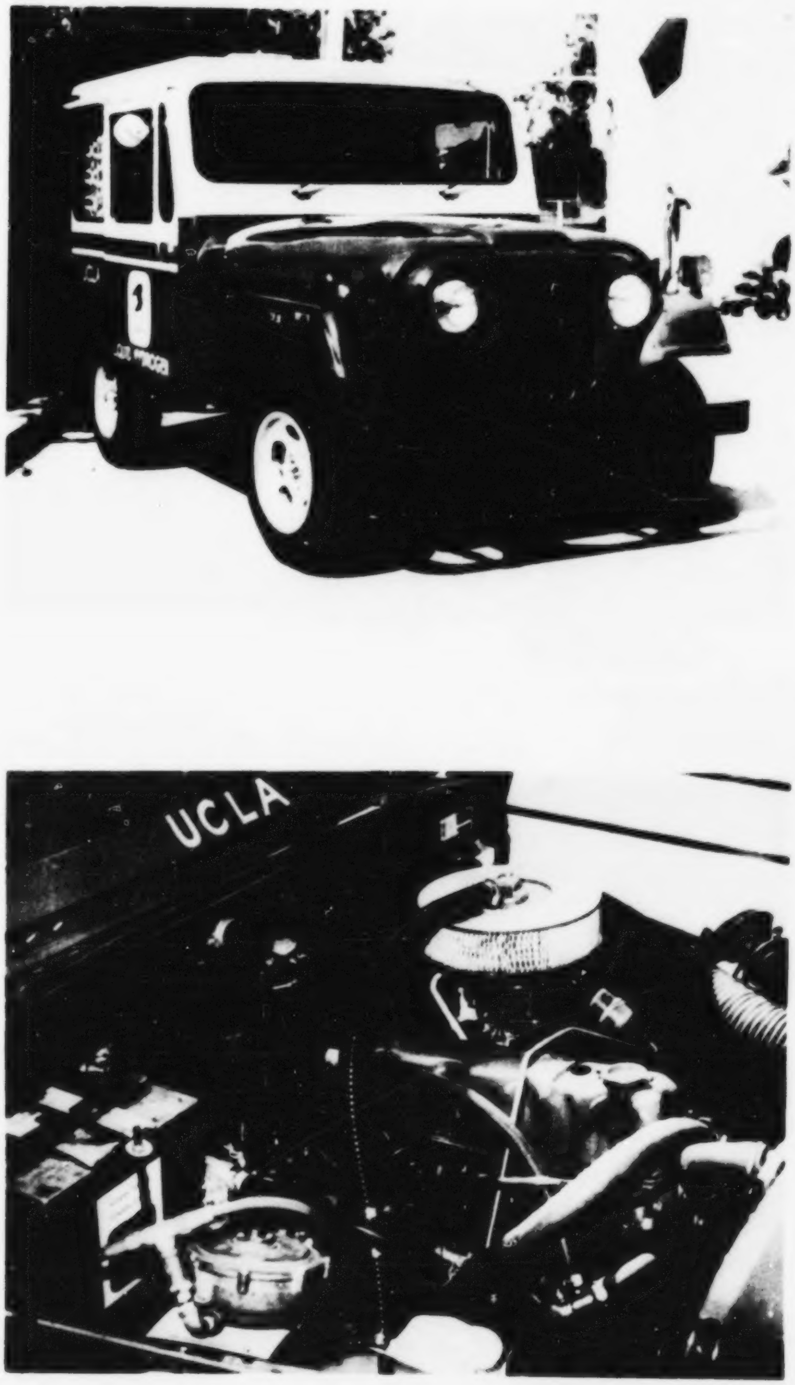

Figure 4 - UCLA/DOT Liquid Hydrogen Fueled Jeep

Economics and Time-of-Availability of Hydrogen

		$\$/10^9\ J^{(a)}$	
	1985	2000	2020
Gasoline from Domestic Crude (Ref.)	3.75	5.36	8.55
Gasoline/Distillate Oil from Coal (b)	4.4	6.00	6.84
Gasoline/Distillate Oil from Oil Shale (b)	4.15	6.44	7.60
H_2 (gas) from Nuclear Heat (hydride storage) (c)	--	6.63	6.63
H_2 (liquid) from Nuclear Heat (insulated tank) (d)	--	8.17	8.17

Notes:
(a) Late 1973 dollars
(b) In a nominal mix of gasoline and distillate oil; no discrimination between the two within accuracy of study
(c) Production is via thermochemical processes at 50 percent thermal efficiency (2000) and 55 percent (2020)
(c) Liquefaction process efficiency assumed at current levels essentially since avenues for improvement remain unidentified at this time (though possible technically)

Reference: J. Pangborn and J. Gillis, "Alternative Fuels for Automotive Transportation -- A Feasibility Study," Final Report EPA-460/3-74-012, Volume II (Technical Section) by the Institute of Gas Technology for the Alternative Automotive Power Systems Division, U.S. Environmental Protection Agency

Table 1 - Cost of Alternative Fuels at the Service Station (ex Tax)

The fact that non-fossil energy derived hydrogen will likely remain considerably higher in cost than alternative hydrocarbon fuels dervied from coal and oil shale is evidenced in Table 1 taken from Reference 3. Nevertheless, it can be seen that, as the cost of extracting increasing more difficult to obtain fossil resources rises with time, comparatively the nuclear derived hydrogen becomes increasingly competitive in cost. The hydrogen costs shown here include the delivery system capital investment which is much more substantial for hydrogen than for the "conventional" hydrocarbon fuels. The latter enjoy the very significant advantage of being able to utilize our present fuels delivery system (tanks, pipelines, trucks, etc.) right down to the vehicle servicing pumps.

Any cost disadvantages for hydrogen may be substantially countered by hydrogen's improved energy conversion efficiency potential vis-a-vis conventional fuels. Improvements in automotive driving cycle applications of 30 to 50% have been recorded or otherwise estimated by various researchers.

Concluding Observations

A number of specific observations are offered to conclude the paper, based on the foregoing discussion and on the various investigations carried out to date, that relate to the potential of hydrogen fuel for surface transportation systems.

(1) As time progresses, there will be increasing recognition of the implacable need for non-petroleum-based, and eventually, non-fossil-based alternative fuels for energy sectors.

(2) The Hydrogen-energy concept. in which hydrogen and oxygen produced from water by means of primary energy sources such as nuclear and solar, will be distributed as a universal "energy carrier," is entirely consistent and in harmony with the above-mentioned need (Item 1).

(3) Production, distribution and utilization of Hydrogen Energy appears to be entirely feasible technically, with acceptable safety levels, based on experience to date in industry, especially in the aerospace sector, e.g. Apollo Program.

(4) Hydrogen's low volumetric energy density (J/L) and, if liquid hydrogen is embraced, its deep cryogenic nature (21 K) pose substantial, but not prohibitive, impediments to its general use as a transportation fuel.

(5) On the other hand, hydrogen's unexcelled gravimetric energy density (J/kg), excellent combustion and cooling characteristics, and its intrinsic low-pollution nature provide strong incentives for its being embraced by the transportation sector.

(6) Onboard vehicle storage of hydrogen requires a considerably more sophisticated and operationally complex containment means than presently used hydrocarbon fuels: either highly insulated tank and associated items for cryo-hydrogen, or metal hydride bed with heat exchange means for hydride storage.

(7) Most powerplants used in transportation vehicles are fully amenable to conversion to hydrogen fuel, but generally require substantial redesign for performance optimization, e.g. water injection, exhaust gas recirculation, or direct-cylinder injection for internal combustion reciprocating engines.

(8) Emissions of consequence to air quality maintenance are limited in a hydrogen airbreathing engine to the oxides of nitrogen and, possibly, hydrogen peroxide (no carbon monoxide, hydrocarbons, particulates, odors, etc.).

(9) Economically, fuel cost per unit of energy ($/GJ) is the significant criterion; hydrogen is likely for several decades to remain significantly more expensive than either petroleum-based fuels or, even, alternative fuels derived from coal and oil shale. However, its advantageous "energy efficiency" and environmental gains can mitigate this increment substantially.

(10) Because the private automotive transportation sector requires

the widest-reaching fuel logistics system of all, with associated large capital investment needs, the private automobile adapted to hydrogen fueling will occur later than hydrogen-fueled aircraft, marine vessels, rail and guideway systems, and public-service/commercial vehicles (buses, trucks, fleet vehicles).

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The short and medium-term development and practical application of hydrogen-powered vehicles*)

Dr. Helmut Buchner
Dr. Helmut Säufferer
c/o Daimler-Benz AG, 7000 Stuttgart-60, Postfach 202
Abteilung (Department) E 6 T - Forschung

At the present level of technology vehicles using hydrogen as a fuel can be employed only for special applications, e.g. urban transport systems. Equipped with TiFe hydride storage tanks these vehicles are superior to electrically-powered vehicles. The application of the so-called gasoline/hydrogen hybrid operation on a medium-term basis is only possible in conjunction with a development of the hydrogen infrastructure. Possible ways for future developing the hydrogen-powered vehicles are discussed.

Dans l'état d'avancement actuel de la technique, les véhicules à hydrogène ne peuvent être utilisés que dans des cas particuliers.

Les véhicules urbains, équipés d'hydrure de TiFe comme accumulateur d'énergie sont d'ores et déjà supérieurs aux véhicules électriques. A moyen terme, l'adoption de véhicules à alimentation hybride essence/hydrogène n'est réalisable qu'avec l'extension simultanée de l'infrastructure pour l'hydrogène. Les possibilités futures de mise au point de véhicules à hydrogène sont à l'ordre du jour.

Kraftfahrzeuge mit Wasserstoff als Kraftstoff können beim gegenwärtigen Stand der Technik nur in speziellen Fällen - innerstädtische Fahrzeuge - Anwendung finden, wobei sie mit TiFe-Hydridspeichern den Elektrofahrzeugen schon heute überlegen sind. Die mittelfristige Anwendung im sogenannten Benzin/Wasserstoffmischbetrieb ist nur mit einem gleichzeitigen Ausbau der Wasserstoffinfrastruktur realisierbar. Zukünftige Entwicklungsmöglichkeiten für Wasserstoffahrzeuge werden diskutiert.

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*) Sponsored by the Federal Minister for Research and Technology

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Hydrogen as a fuel for internal combustion engines has been well known for a long time now. In view of the energy situation and the problems of environmental protection the question of hydrogen as an alternative fuel to gasoline has recently been thoroughly discussed. Mention must be made in this connection of the following essential features:

- Hydrogen is available in unlimited quantities as it can be produced from water, using nuclear power.
- Owing to the water - water/oxygen - water cycle no additional oxygen need be supplied.
- Hydrogen is completely non-poisonous.
- Conventional internal combustion engines require only limited design changes which allow for the high ignition quality and flame speed of hydrogen.
- The combustion efficiency in the engine is the same or even better than in the gasoline engine.
- During the hydrogen combustion in the engine practically no CO or CH emission is observed.
- The problems of lead emission are bypassed, sulphur dioxide and smoke emission does not occur.
- Owing to the wide ignition range of hydrogen/air mixtures low NO_x values can be obtained.
- Gasoline/H_2 hybrid operation is possible with any mixing ratio.
- Because of the complete lack of an infrastructure for hydrogen a complete substitution of present-day internal combustion engines in vehicles for pure H_2 engines is, however, impracticable for the next 20 years; in fact, even the key problem, i.e. the storage of hydrogen in the vehicle, has not been solved satisfactorily up to now.

With these points in mind the hydrogen-powered vehicle definitely cannot be regarded as an alternative solution to gasoline-powered vehicles in the near future. Special applications, however, are possible. Considering the facts:

- hydrogen can be produced centrally today from coal or natural gas at a favourable price,
- hydrogen-powered engines have particularly favourable anti-pollution qualities, and
- hydrogen can be stored much better than electrical energy

there is a possibility of converting city transport systems entirely to hydrogen-powered vehicles within the next few years as city transport vehicles with exhaust emission control can be operated much more favourably with a hydrogen drive train (hydrogen storage tank - internal combustion engine) than with an electric drive unit as previously.

The storing of hydrogen in metals and alloys (hydrides) for vehicular applications has evoked great interest in the last few years as this technique avoids the disadvantages of storage in gas cylinders (high pressure, considerable weight and large volume) and storage in liquid form (high consumption of primary energy for liquefaction, extremely low temperatures, problems of insulation and design of the cryogenic tank).

Titanium-iron-hydrogen alloys, for instance, are capable of storing about 30 times the chemical energy of a lead acid traction battery. According to Wiswall and collaborators (1) the alloy TiFe has two hydrogen phases, namely, TiFeH and $TiFeH_2$ with storage densities of up to 670 Wh/kg. Both hydrides are formed exothermally. The binding forces are -30 kJ/mol H_2 ($TiFeH_2$). Titanium-iron alloys are therefore compounds which are chemically very unstable and allow for an easy absorption or desorption of the hydrogen.

Figure 1 shows the characteristic temperature/pressure curves for two titanium-iron alloy hydrides and in this connection particular stress shoud be laid on the following points:

- At a working temperature of about 20°C the pressure in the storage tank is between 4 and 9 bars depending on the hydrogen content with the result that the safety requirements can be restricted to a minimum.
- At low temperature between about -10°C and -20°C a pressure of more than 1 bar is reached depending on the hydrogen content so that there is a continuous hydrogen supply also during cold start.

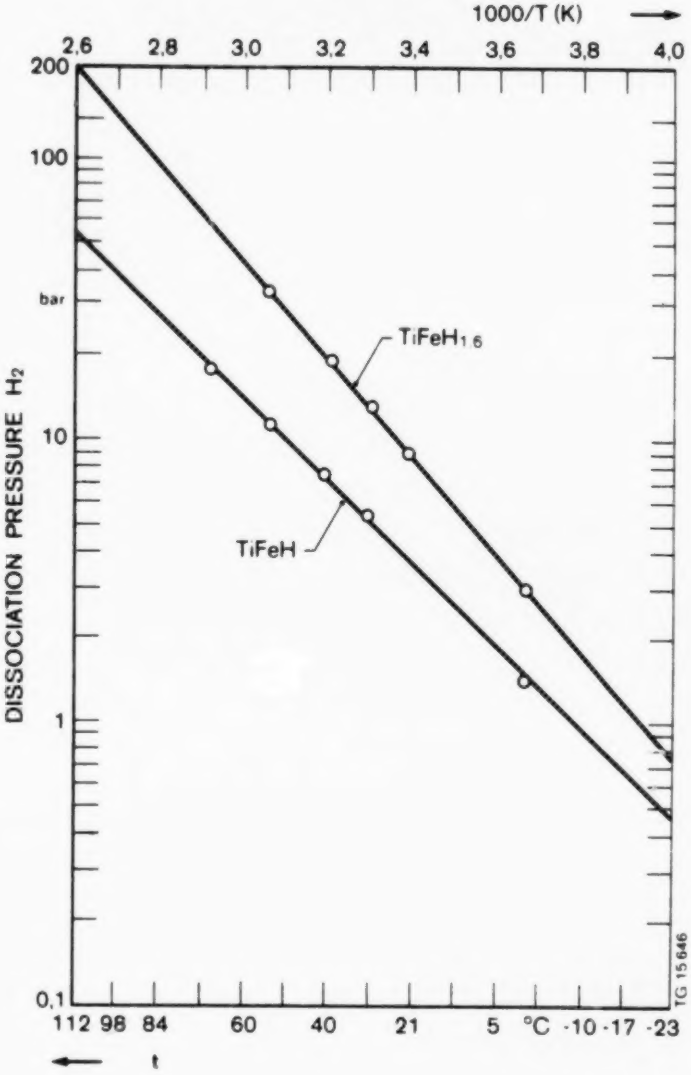

Fig. 1: Dependence of plateau-pressure on temperature

The consumption of a 75 KW engine at full load lies at about 1 mol H_2/s. In the case of the titanium-iron hydrides the storage tank should be supplied with a heat quantity of 30 kJ/s to allow for a continuous supply of hydrogen at a pressure of >1 bar. The required amount of heat is contained in the cooling water which absorbs about 25% (60kJ) of the combustion heat generated per second by the engine. The hot engine cooling water should therefore be routed past the storage tank in such a way that the heat can be transferred into the interior of the storage tank. This requirement is dependent only on the thermal conductivity of the tank. For a given weight and volume of the storage tank it follows that cylindrical containers should be as long as possible and relatively small in diameter. Owing to their porosity the alloy powders to be discussed here have a considerably lower heat conductivity than solid-state bodies. First experimental results (obtained in the DB-laboratory) concerning the TiFe storage tank have shown, however, that the heat conductivity is large enough to ensure the required transfer of heat even at full load. At partial load and idling the consumption is lower than under full load conditions. Thus the storage tank can adapt itself quickly to any driving condition. - The low temperature properties (from -20°C onwards) could be improved either by distorting the crystal lattice of the titanium-iron hydride by means of foreign metal atoms thus increasing the hydrogen dissociation pressure or by developing a hydride as a "starting aid" that is particularly unstable at low temperatures. Heating up of the tank by hydrogen-air combustion on the outer wall of the tank would be possible but within the vehicle itself hardly practicable. Direct comparison shows that even in the low temperature range the TiFe storage tank is already far superior to the lead acid traction battery. Improvements in the heat conductivity and dissociation pressure values are of particularly decisive importance if the hydrogen engine is to be operated to the diesel principle. The required high-pressure hydrogen (60 bars) could then be taken directly from the storage tank so that one could do without technically complicated compressors which, for instance, would be required in the case of liquid hydrogen in conjunction with the high-pressure injection process and which in terms of energy are highly unfavourable.

Table 1 now shows a direct comparison between an electric drive train (with lead batteries) and a hydrogen drive train with a TiFe hydride storage tank. Mention must be made here in particular of the 5 to 6 times greater range of operation given the same storage weight, the considerably reduced storage volume (factor 2 as compared to lead batteries), the maintenance-free design, the short refuelling times and the much lower cost of the hydrogen drive due to the improved service life and larger payload space (table 2).

	$TiFeH_{2-x}$	Pb-Accumulator
storage density (Wh/kg)	570 - 670	20 - 25
efficiency	20% (I.C.engine)	60% (electromotor)
proportion of range at constant storage weight	6 :	1
proportion of volume at constant range	10 :	1
working pressure (bar)	1 - 20	1
working temperature	-20°C - +100°C	-20°C - 50°C
self discharge	none	yes
maintenance	none	yes
lifetime	unlimited	very limited
charging time	5 - 15 min.	> 1 h
charge efficiency	100%	80%

Table 1: Comparison Hydride-/Electric Propulsion

	$TiFeH_{2-x}$	PB-Accumulator
storage weight (kg)	300/365+)	1400
range (km)	50	50
max. payload (kg)	2135++)	1100++)
lifetime (years, 250 cycles/year)	> 6	< 6
lifetime capacity (t.km)	> 162 000	< 84 000
spec. costs of materials (DM/kg)	10	12
total costs of materials (incl. interest) (DM)	5000	27 000
costs of maintenance (DM)	-	7500
costs of energy (DM)	5400+++)	5300++++)
total costs (DM)	11000	40000
costs per t.km (max. payload) (DM)	0,07	0,47

+) incl. pressure tank

++) payload + storage weight 2500 kg

++) 6 Pf/Nm^3 H_2

++++) 10 Pf/kWh

Table 2: Comparison of Economy (Hydride-/Electric Propulsion)

As even optimistic forecasts for electro-chemical storage systems (e.g. sodium-sulphur batteries, 380°C operating temperature, corrosion protection!) do not appear to suggest that these values can be reached by electrically-powered vehicles, the hydrogen drive with non-optimized hydrides is now even superior to the optimum conceivable electrically-powered vehicle.

It is assumed in connection with this that the complete lack of exhaust on electrically-powered vehicles which is a requirement for operation in enclosed spaces, can be dispensed with in urban traffic in favour of economy, range of operation and vehicle weight.

A further application of hydrogen storage in metal hydrides is the gasoline/hydrogen hybrid drive in the vehicle. As compared to pure gasoline operation, gasoline savings of up to 25% (table 3) and a very low NO_x and CO content in the exhaust can be expected in this case.

		Gasoline	$TiFeH_{2-x}$		Hydride with 3,6 wt % H_2	
Hydrogen	(kg)	-	2,3	4,6		
Gasoline	%	100%	86%	75%	86%	75%
Storage weight	(kg)	-	130	260	65	130
Storage volume	(l)	-	30	60	15	30
Total weight	(kg)	52	175	300	110	170
Total volume	(l)	65	85	110	70	80
Heating value	(kWh)	600				
Exhaust			improved+)	impr.+) subst.+)	impr.+)	improved substantially+)
Saving rates of Hydrocarbons		none	15 - 25%		15 - 25%	

+) related to standard values of gasoline engine

Table 3: Comparison Gasoline-/Gasoline/H_2-Propulsion

When using the presently availabe titanium-iron hydride, a tank system of this kind would have a volume of ~ 100 litres and a weight of between 200 and 300 kg. A hydride with a hydrogen storage density of between 3 and 4% by weight - the devlopment of which seems quite possible within the next few years - would reduce the total tank weight and the total tank volume to less than 150 kg and 70 litres respectively. The presently well-known Mg_2Ni-hydride with an H_2 content of 3.3% by weight is less suited for technical applications because of the increased binding forces of the hydrogen in the lattice (-60 kJ/mol H_2) and the low

dissociation pressure in the range of up to 100°C. -
Particular attention should be drawn to the fact that hybrid operation on a gasoline/hydrogen/air basis requires per time unit only about 1/10 of the amount of hydrogen which is needed for pure hydrogen operation. In the case of gasoline/hydrogen operation therefore the normally required external heat supply to the storage tank is omitted thus simplifying the complete **system.**

As gasoline and hydrogen can be be mixed in any proportion, hybrid operation can be regarded as the transition stage between pure gasoline and pure hydrogen operation technology for all types of vehicles. The production and distribution of hydrogen could be adapted to the stage of development of the hydrogen-powered vehicle. This would enable a gradual transition to a hydrogen technology on a long-term basis. -
With a 25% saving on gasoline and approximately the same tank volume, the gasoline/hydride tank system is still 2 - 3 times heavier than a similar tank for a gasoline/methanol hybrid system but the emission values are much more favourable than on the gasoline/methanol version. For this reason gasoline/hydride operation would be particularly suitable for buses operating in urban areas. The relatively small hydrogen quantities which would be required for this purpose could be definitely obtained from central filling stations.
There are two possible versions of this type of filling station. In the case of on-board fuelling the storage system remains in the vehicle. Gaseous hydrogen reacts with hydride powder at a pressure of about 50 bars. The heat which is released during the reaction within a few minutes would heat up the TiFe storage tank by about 500°C. As, however, the hydrogen dissociation pressure at temperatures above 100°C is higher than the available hydrogen pressure, quick on-board fuelling would only be possible if a powerful water cooling system is used and if the heat conductivity of the storage material is satisfactory. Preliminary tests (in the DB laboratory and in the Brookhaven National **Laboratories**)(2) have shown that heat-consuming ordering effects (superstructure!) occur in the crystal lattice during hydrogenation. The values are so high that under the specified conditions up to 6/7 of the total possible hydrogen

quantity can be absorbed without external cooling. During this process the storage tank heats up by only 60 - 70°C. Fuelling times of a few minutes are therefore quite possible in the case of titanium-iron hydrides even if no additional cooling elements are employed. The fuelling time depends basically only on the cross-section of the hydrogen feed line.
If during the further development of the hydrides a material with high hydrogen density should be developed which does not have this latent heat storage effect, either the internal heat conductivity and the external cooling of the storage tank would have to be improved considerably or the "material exchange" filling system would have to be used.
In the case of the "material exchange" filling system the exhausted storage material is drained from the tank which remains in the vehicle and fresh hydride powder is filled into the tank. This system which is very similar to the present-day filling method, offers two great advantages:

- The tank in the vehicle only needs to withstand low pressures and therefore a considerably lighter construction can be used. The filling pressure of the powdered hydride should correspond only to the operating pressure in the tank (in the case of titanium-iron hydride approx. 20 bars).
- The time taken to recharge the storage material in the filling station is unimportant since the vehicle does not have to wait For this reason, the charging pressure (hydrogen gas line pressure) needs only to be slightly higher thank the operating pressure. In addition to this, no particular cooling measures need be taken as only little heat is devloped per unit of time.

Only the methods of storing additional quantities of storage substance which is required by this system could be a disadvantage (investment costs!).

Compared to the first two fuelling methods, exchanging the complete storage tank for a full hydrided one, as in the case of electric vehicles today, is impractical since not only additional investment cost will be needed for the exchange tank,but also all lines leading to the engine (gas and cooling water lines) would have to be disconnected.

Summary

The level of present-day technology, the energy situation and environmental protection would seem to suggest that a gradual introduction of a hydrogen technology would be feasible along the following lines:

- Owing to the relatively low hydride storage densities the application of hydrogen engines in urban transport vehicles (delivery vans, replacement of electric vehicles) is envisaged for the near future (up to 1980).
- If, and this appears quite possible, the storage capacity can be doubled or tripled in conjunction with an improvement in the hydrides, then hydrogen engines could be introduced by 1990 for trucks and buses or could be generally applied as hybrid drives for cars powered with hydrogen as an additional fuel. In addition to gasoline, all hydrocarbons, e.g. methanol and methane, can be used as base fuel.
- In the long run the hydrogen engine could only be generally introduced, particularly on cars, if either

  the hydride storage density can be considerably improved (factor of 4 - 5 times compared to the present-day hydrides for vehicular application) or

  sufficient primary energy is availabe for the production and liquefaction of hydrogen.

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SESSION 3

Component Development

3ème SESSION

Développement de composants

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Ford Vehicular Gas Turbine Ceramic Regenerator Durability Development Program

G. PEITSCH - A. F. MC LEAN
Ford Motor Company
20000 Rotunda Drive
Dearborn, Michigan 48121

This paper summarizes the experience Ford has had with ceramic regenerators in gas turbine engines and describes Ford's on-going program to improve the reliability and durability of the ceramic regenerator system. Test results and developmental status of both basic materials and complete systems are reported.

INTRODUCTION

The purpose of this paper is to summarize the experience that Ford has had with ceramic regenerators in gas turbine engines, and to describe Ford's ongoing program to improve the reliability and durability of the ceramic regenerator system.

HISTORY

Ford Motor Company has been running lithium-aluminum-silicate (LAS) ceramic regenerator cores in gas turbine engine applications since 1965. More than 100,000 hours of engine operation on almost 1,000 regenerator core samples from two different suppliers were accumulated between 1965 and the end of 1973.

Much of this operating experience was gained during the development of Ford's 350 to 450 hp model 707 industrial gas turbine engine. The model 707 engine was a low pressure ratio, variable nozzle, two shaft machine with dual regenerators.

By mid-1971, when Ford started limited volume production of the 707 engine, we believed that we had total system reliability and durability adequate to meet the market requirements for this engine. Many of the initial installations were on standby electric generator sets and pleasure boat installations. Several engines were also installed on Ford trucks operating between plants in the Great Lakes area.

Because of unexpected sporadic failures of the ceramic regenerators in a variety of applications, a new set of controlled durability confirmation tests was initiated during January, 1973. Twelve engines were placed on test on dynamometers, in generator sets, and in highway vehicles. When this test was terminated in August of 1973, 11 regenerator core failures had occurred out of a total of 30 cores tested. These failure data were plotted on Weibull curve paper as shown on Figure 1. From this curve, it can be seen that the B_{10} life (the life which 10% of population will have failed) was only 500 hours, and the

Fig. 1 "Statistical Life of Regenerator Cores"

B_{50} life was only 1500 hours. This level of reliability and durability was far below the design specification requirement for initial entry into commercial markets. Accordingly, production of the 707 engine was halted in mid-1973.

From the controlled test data that had been accumulated, we were able to identify the primary cause of failure of the ceramic regenerator cores. It was determined that many of the failures were due to severe chemical attack of the particular lithium-aluminum-silicate (LAS) material used in building the core matrix. The chemical attack is from sodium and sulphuric acid. Sodium is ingested into the engine's intake system when operating in a marine atmosphere, or when operating trucks on salted roads during winter months. Sulphuric acid is formed as a product of combustion when high-sulphur diesel fuel is utilized.

The two major failure modes of an LAS regenerator, rim break-up and mid-radius cracks can now be predicted on a computer and shown to be the result of thermal stresses due to the thermal restraint of the rim. Rim break-up is usually caused by poor material properties, poor fabrication, or over-temperaturing during operation. Mid-radius cracks are caused by sodium or sulphuric acid chemical attack which changes the matrix material expansion properties. Both types of failures can be correlated on the basis of rim thermal stress safety factor, which is the ratio of the strain tolerance divided by the thermal expansion over the operating temperature range.

Historical data accumulated also indicate that LAS cores with high thermal stress safety factor due to extremely low expansion characteristics will fail after high hour accumulation because of chemical attack. This type of failure will occur after enough lithium oxide has been removed by sodium or sulphuric acid so that the material integrity has been lost.

Based on the test and analysis of material property degradation done to date, it is believed that a core which is relatively impervious to sodium and sulphur attack would meet our life requirements if the factor of safety were equal to or greater than 1.0.

In late 1973, Ford initiated a major program to improve the reliability and durability of an engine waste heat recovery system using a rotating ceramic core. While this program is directed primarily at developing a new regenerator matrix material, improvements in core construction and in the regenerator support and drive system are also considered necessary to achieve program objectives.

DURABILITY PROGRAM OBJECTIVES

The primary objective of the Ford program is to develop ceramic regenerator systems that can be used in industrial and/or vehicular turbines of the 707 type, in Stirling Cycle engines, and in high temperature passenger car engines. The 707 engine is being used as a test bed to verify the results of laboratory experiments.

Specific durability objectives are defined as achieving a B_{10} life of 10,000 hours on an industrial and/or vehicular duty cycle with a turbine inlet temperature of 1000° centigrade. These objectives will be correlated with the life cycle required for other types of engine applications. For example, a B_{10} life of 10,000 hours under the specified test condition is projected to translate to 3,500 hours in a high temperature passenger car turbine engine, which is the equivalent of 100,000 mile durability in passenger car usage.

As reported in Ann Arbor on May 14, 1974, we are also working with the Environmental Protection Agency to develop a ceramic regenerator which will meet the requirements of both the EPA/Chrysler Modified Baseline Engine and the EPA/Chrysler Upgraded Engine. This regenerator is to be capable of operating at temperatures up to 800°C and is to obtain a B_{10} life of 3,500 hours on a passenger-car duty cycle. It should be capable of operation on either No. 1 or No. 2 diesel fuels as well as non-leaded gasoline.

The matrix material must be capable of providing the following performance in a full size core: The core thermal stress factor of safety must be equal to or greater than 1.0; the material must be stable within 100 ppm after 10,000 hours at 800°C; and the material must be virtually impervious to ion exchange (less than 20% loss of initial magnesium or lithium in 10,000 hours).

To screen the various materials prior to full scale testing, the following monitoring criteria are being used. The thermal stress safety factor can be calculated from the material strength and expansion properties. Resistance to sodium and/or sulphuric acid attack is determined by laboratory experiment. A test bed 707 engine is being used for accelerated contamination testing by utilizing road salt ingested into the intake air system, and artificially high sulphur fuels.

In addition to durability objectives, a reasonable production process must be developed to meet the cost requirements of both the high volume passenger car engines under study and lower volume industrial/truck turbines. Again, the 707 engine will be used as a baseline for projecting high volume regenerator core costs of the smaller engine. Suppliers must monitor their process and manufacturing procedures as they develop a suitably durable core to assure meeting long range cost projections.

In parallel with the durability effort, a certain amount of performance optimization will also be carried out. Trade-offs between effectiveness and pressure drop are allowable and will be considered in the final configurations selected for the passenger car programs.

PROGRAM STATUS

As mentioned earlier, an engineering research program was initiated late in 1973 to solve the regenerator core failure problem. Work plans were prepared based on a two-year program to solve the problems identified during the 707 turbine program. The 1974 program, which is now 75% complete, is concentrating on developing a new magnesium-aluminum-silicate (MAS) ceramic matrix material which will meet the engineering requirements for strength, durability, performance, and cost. During the remainder of 1974 and for the entire calendar years 1975 and 1976, a concentrated dynamometer durability test program will be used to verify the corrective actions taken by the regenerator core suppliers in meeting the Ford objectives. Additional testing could extend into 1977, depending on overall program success.

Ford is working with four outside companies to develop materials and processes. Corning Glass and GTE Sylvania have excellent materials research capability. Coors Porcelain and W. R. Grace Company have excellent fabrication and processing capability, which should lead to an acceptably low-cost component All four companies gained considerable experience on the MAS (cordierite) family of ceramics during their catalytic muffler subtrate programs. It is this background of technology that will contribute to the success of the regenerator core activity sponsored by Ford.

To assist and support the four suppliers, Ford Scientific Laboratory is conducting basic research in the low expansion MAS ceramics and in polymer research to support the bonded ring gear and binder-plasticizer systems that are required to fabricate cores by a low-cost calendering procedure.

The overall engine test program for 1974 is shown in Figure 2. It is expected that a decision on the success of the regenerator core program will be possible by year-end 1975. However, the full 10,000 hours of test time will require a continuous 20 months of operation which could extend through June, 1977.

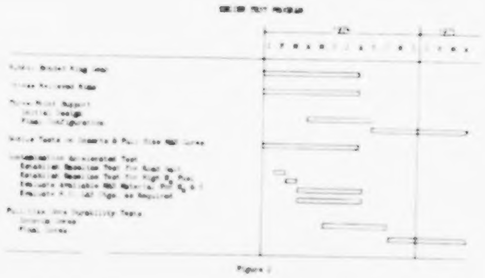

Fig. 2 "Engine Test Program"

MATERIALS TEST AND DEVELOPMENT

Laboratory tests on both LAS and MAS materials have shown that MAS is virtually impervious to sodium and sulphuric acid attack. These results were confirmed in engine tests where cores containing inserts of MAS and LAS material were exposed to ingested road salt. The LAS materials showed a significant deterioration in material properties. Of the seven different MAS materials evaluated in these engine tests, five showed no effect at all from the ingested road salt. The worst MAS material evaluated in these tests showed only 1/5 the material properties deterioration of the original LAS materials. The chemical attack resistance was independent of wall thickness and number of openings per inch. The samples with lowest porosity, however, were more resistant to deterioration.

Excellent progress has also been made in achieving the required strength and expansion properties of the cordierite materials and several candidates are considered suitable for full size core evaluation. Corning Glass has also had some success in preventing chemical attack in their LAS material and full size cores of this type will also be evaluated.

ELASTOMER BONDED RING GEAR

The bonded ring gear using an elastomer material developed by Ford and Dow Corning is required to both reduce rim thermal stress and manufacturing cost. Thirty-four ring gears bonded to cores have been tested in 1974, with two bond failures occurring at 930 and 2042 hours. Five have accumulated over

2,000 hours, with 3,000 hours being the longest service to date.

STRESS RELIEVED RIM

Several different configurations designed to relieve stress of the rim are now on durability test, using the original LAS core material. Since this material is subject to chemical attack from sulfur in the fuel, it was expected that failures would occur as mid-radius cracks. While the stress relief is principally effective at the rim, there is some relief at the mid-radius. Preliminary results from a 12 sample test do indicate improvement in mid-radius cracking due to the stress relieving design as shown in Figure 3. Further analysis of this stress relief technique for additional optimization is a continuing program and these results will be incorporated in the MAS cores.

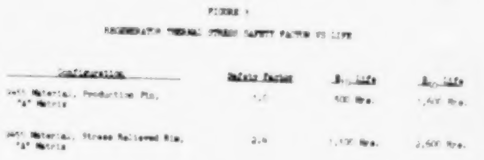

Fig. 3 "Regenerator Thermal Stress
Safety Factor vs Life"

THREE-POINT REGENERATOR CORE SUPPORT AND DRIVE SYSTEM

In the original design the core is mounted on a central shaft with a solid ceramic hub bonded into the ceramic core. A metal ring gear attached to the rim of the core provided a drive. Since this design produces stress at the hub due to support and driving forces, a new system is being developed in which the ring gear is supported externally by rollers, thereby eliminating the need for a solid hub and simplifying fabrication of the core, as well as reducing stresses. Three engines with prototype rim-mounted core configuration are now on test. About 350 hours have been accumulated on one core using this drive system.

DYNAMOMETER TEST RESULTS AND STATUS

Approximately 12,500 hours of engine running time were accumulated by October 1, 1974. These test hours served to evaluate the chemical attack resistance of MAS matrix samples, the various stress relieved rim concepts and the elastomer bonded ring gear system. The three point support core drive system was also tested and refined so that it is now ready for durability verification testing with full size hubless MAS cores.

Full size continuous wound MAS cores have been tested from three of the four suppliers. Two MAS cores have reached over 200 hours of engine operation indicating good thermal performance and seal compatibility, even though this MAS material was of an early vintage not meeting our requirements for strength and expansion.

FABRICATION DEVELOPMENTS

Cracking of full size 71.12 centimeter diameter MAS cores during firing is considered the major problem at this time. The problem has been defined as related to binder burnout, and considerable progress is being made by all the suppliers.

Overall, the technical achievements are on schedule and it is expected that 71.12 centimeter diameter cores of the latest material which meet our specifications will be available for engine evaluation by November of this year as shown in the timing chart, Figure 2.

Compact Gas Generator for the Economic Operation of Internal Combustion Engines with Low Pollutant Emission*)

W. FRIE, H.-J. HENKEL, H. KOSTKA, W. KÜSEBAUCH, A. MICHEL,
B. PAUL, E. v. SZABÓ

SIEMENS AKTIENGESELLSCHAFT
Forschungslaboratorien Erlangen

Dynamometer measurements carried out on a gas generator and internal combustion engine combination have shown that, when a gas fuel containing sufficient hydrogen and carbon monoxide is used, pollutant emission can be greatly reduced without increasing fuel consumption, or fuel consumption can be greatly reduced if emission is cut back only slightly in comparison with emissions from an engine with a conventional carburetor.

Les mesures au banc d'essais effectuées sur une machine à combustion interne, alimentée à partir d'un générateur de gaz, ont prouvé qu'avec un gaz combustible ayant une teneur suffisante en hydrogène et en monoxyde de carbone, il était possible d'obtenir, par rapport à l'alimentation par carburateur conventionnel, soit une forte diminution de l'émission spécifique de gaz toxiques sans entraîner pour autant une augmentation de la consommation de carburant, soit une forte diminution de la consommation accompagnée d'une réduction moins sensible de l'émission de gaz toxiques.

Prüfstandsmessungen an einer Kombination Gasgenerator-Verbrennungskraftmaschine haben ergeben, dass mit einem Brenngas von hinreichendem Wasserstoff- und Kohlenmonoxid-Gehalt eine starke Absenkung der spezifischen Schadstoffemissionen ohne Erhöhung des spezifischen Brennstoffverbrauchs oder eine starke Absenkung des Verbrauchs bei geringerer Reduktion der Schadstoffemissionen im Vergleich zum konventionellen Vergaserbetrieb möglich ist.

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*) Sponsored by the Federal Minister for Research and Technology

1. Introduction

In contrast to conventional carburetor engines, gas engines can be operated far into the lean region, due to the homogeneous miscibility of fuel gas and air. One of the advantages offered by lean running is that the pollutant concentration in the exhaust is greatly reduced without any increase in fuel consumption /1/. The fuel gas must be stored either in liquid form or under pressure in cylinders. This gives rise to supply problems and makes it difficult to apply this technique to motor vehicles. It is more economical to produce low molecular fuel gas from easily storable liquid hydrocarbons in the motor vehicle itself.

With regard to a catalytic gas generator designed to supply mobile internal combustion engines, the following goals should be aimed at:

- high efficiency
- low volume and weight
- easy control, even under rapid load changes
- independence of external water supply
- service life of catalyst >300 hours
- operation at atmospheric pressure

2. Gasification processes

These goals indicate that the familiar industrial gasification processes cannot be adopted without modification. Where these processes are carried out in the proximity of thermodynamic equilibrium, they use either a large excess of water or the addition of a large quantity of gasification air ($\lambda \geq 0{,}3$)in order to keep soot formation down to a low level /2/. A maximum efficiency of 70 % may then be expected for operation with air without the addition of water. Furthermore, the achievement of thermodynamic equilibrium requires a long residence time for the constituents in the reactor, thus resulting in a generator of large specific size. In view of these disadvantages, we did not pursue such systems any further /3,4/.

The demands made on a gas generator consequently lead to a largely adiabatic process carried out at atmospheric pressure away from thermodynamic equilibrium with very low quantities of air and eventually with exhaust gas. It is necessary for this type of process that the desired gasification reactions are accelerated by a catalyst of high selectivity and high load capability, and that the gas produced is cooled immediately upon leaving the reactor /5/. A diagram of the process is given in Fig. 1. Fuel, a very small quantity of air ($0.05 \leq \lambda \leq 0.15$) and eventually exhaust gas are preheated, fed to the catalytic reactor at atmospheric pressure, and converted at approximately 820 °C. The product gas is cooled in heat exchangers, mixed with combustion air, and drawn into the internal combustion engine. Where the reciprocal equivalence ratio is less than $\lambda = 0.1$, exhaust recycling is not absolutely necessary because in this region the reaction can be conducted autothermically by λ control. A gasification efficiency of better than 90 % can be achieved. 60 l of gasoline per hour can be gasified per litre of catalyst. Low octane, lead-free gasoline can be used, e.g. straight run, as well as methanol or diesel oil. No catalyst life tests have been carried out in the case of diesel oil.

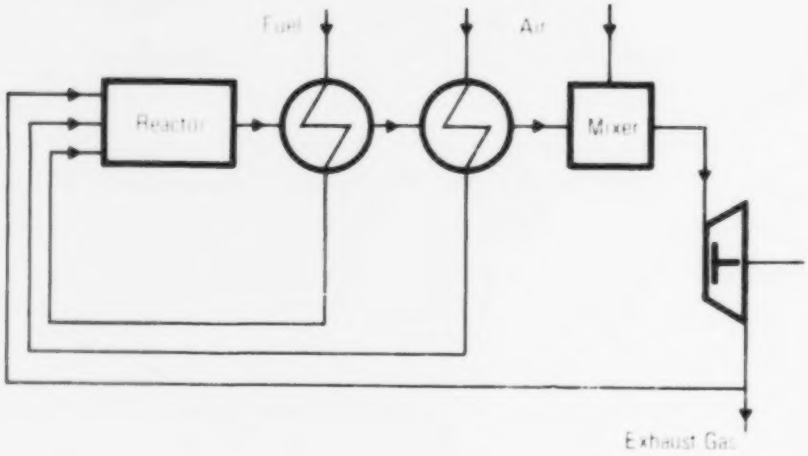

Figure 1. Process schematic of autothermic fuel gasification by partial oxidation

3. Mathematical model of the cracking process

Extending the thermodynamics of chemical equilibrium allows an ongoing cracking process to be divided up with respect to time /6,7/. As soot formation obviously proceeds at a relatively slow rate in comparsion with the other processes, low soot formation can be expected where the input constituents have short residence time in the reaction area. Where this model is concerned, the soot formation limit lies at the point where the primary radicals of the form C, CH, CH_3, CH_2 etc., occur in large quantities. The parameter of this "quasi equilibrium calculation" is the number of molecules containing carbon which are produced from one input hydrocarbon molecule (C_nH_m). This parameter is denoted as the cracking number a .

When a=1 cracking has not yet begun. During the reaction the cracking number increases to a=n, at which point cracking is completed. The reaction time must be selected to prevent the soot formation limit from being reached. Fig2 gives an example for 800°C, n-heptane, and $\lambda = 0.1$. In this case the soot formation limit lies at a=6.2.

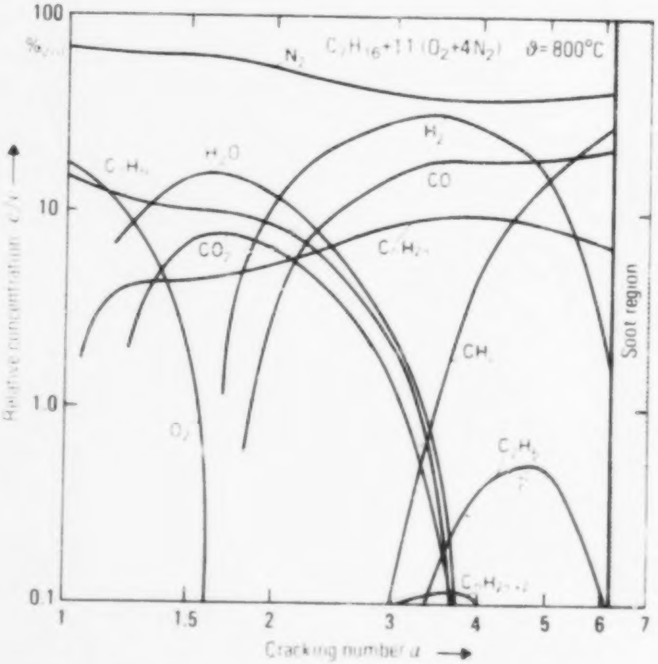

Figure 2. Gas composition versus cracking number

4. Catalyst development

Partial oxidation of hydrocarbons can also be carried out without catalysts, but the catalytic processes are superior because they operate selectively and have a higher yield at the same reaction temperature. The properties of the catalyst used substantially determine the reactor volume and the quality of the product gas.

A selective working catalyst which converts a proportion of recycled exhaust gas has successfully been developed for autothermic partial oxidation of hydrocarbons.

Fig. 3 shows the composition of the gas produced by partial oxidation of n-heptane at a catalyst temperature of 800°C as a function of the concentration of exhaust gas in the oxidant. Attention should be drawn to the small drop in the CO and H_2 content of the product gas with increasing recycling of the exhaust gas.

The posibility of replacing part of the gasification air by exhaust gas enables easy control of the reaction temperature. In operation soot is deposited in the catalyst, which reduces its porosity but does not cause it to become less active. Soot deposition ceases during the first hour of operation. Fig. 4 shows the soot deposition and porosity as a function of time.

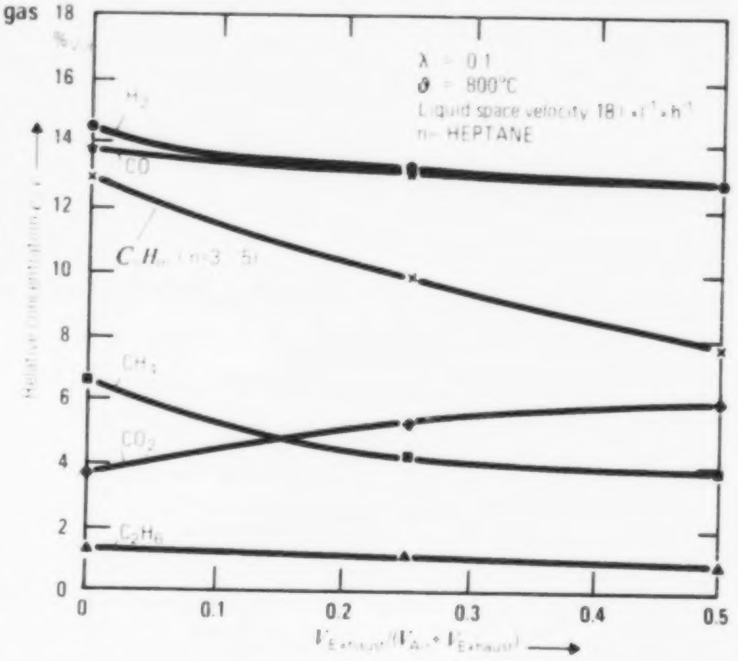

Figure 3. Gas composition versus exhaust gas fraction of the oxidant

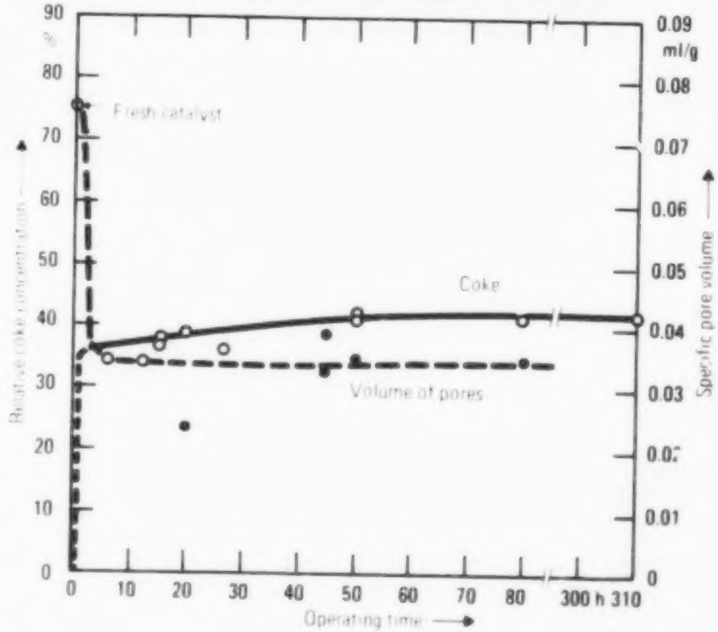

Figure 4. Relative coke concentration and specific pore volume versus operating time

5. Test reactors

The newly developed exothermic and endothermic catalyst is used in cylindrical reactors 10 cm in diameter charged with 250 cc of catalyst. The residence time is 22 ms at a throughput of 10 l/h straight run gasoline and a reciprocal equivalence ratio λ = 0.1.

Fig. 5 shows a reactor of this type in combination with a heat exchanger. A mixer at the reactor inlet serves to distribute the mixture of constituents homogeneously over the catalyst. However, this system is not yet working entirely satisfactorily. The results achieved with small test reactors have not yet been fully achieved with reactors suitable for operation with internal combustion engines. 160 hours of trouble-free operation were obtained, whereas the small test reactors ran trouble-free for 300 hours. But conversion of gasoline fed into the system amounted to only 80 %. A possible cause may be the rapid increase of the flow cross-section at the mixer outlet. The effect of this is that the catalyst in the reactor outer zone is too lightly loaded and that in the central area it is overloaded; so the temperature in the outer zones sinks to 700°C with a corresponding decline in conversion and gas quality. On dynamometer tests therefore either the catalyst temperature was increased, or a significant increase in the quantity of condensate was accepted. Increased conversion can also be achieved by arranging two reactor-stages in series. In this case a proportion of the gasification air is fed in between the two stages.

6. Gas generator and internal combustion engine combination

Experiments were carried out on the dynamometer test bed by using a 1.6 l Volkswagen engine with several gas generator variants and different catalysts. A conversion of 95 % was achieved with a single-stage reactor. In this instance the reactor temperature was 970°C with a gasoline throughput of 14 l/h.

Fig. 6 and 7 provide a comparison of the engine data for operation with gas generator

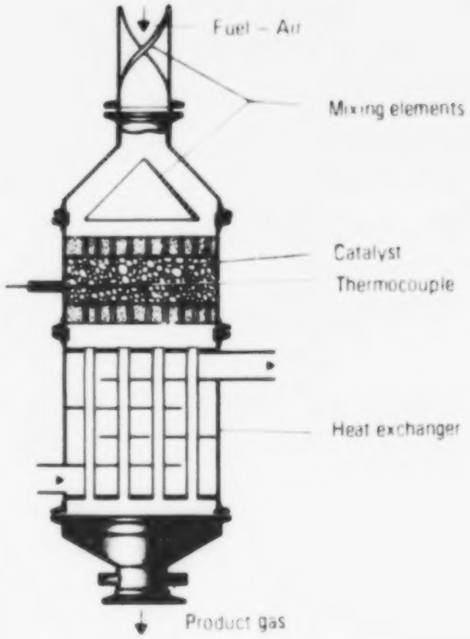

Figure 5. Catalytic gas generator

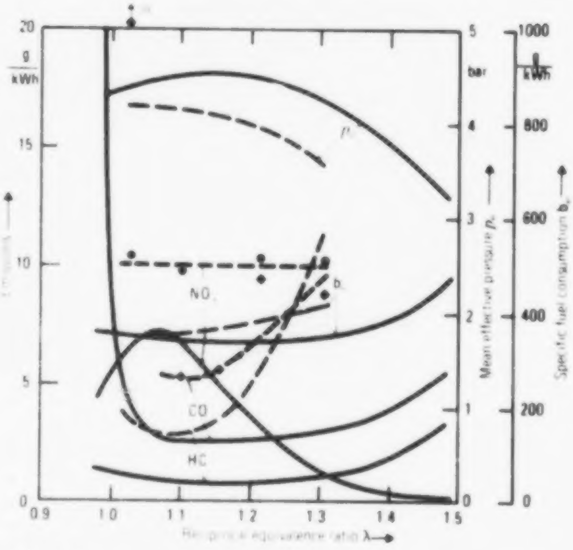

**Figure 6 Comparsion of operation with gas generator ——— and stock carburettor – – –
1.6 l VW-engine, 2000 rpm, α_z = 20° BTDC**

and with a stock carburetor at a gasoline input of 5 – 6 l/h. The product gas quality allows the input to the engine to be made as lean as λ = 1.5 approx. without the CO and HC content of the exhaust gas increasing, and without any rise in fuel consumption. Tests have shown that it is possible to achieve either lower fuel consumption (17 %) with a moderate reduction of pollutant emission (NO_x 1:4), or a substantial reduction of pollutant emission (NO_x 1:30) with the same fuel consumption. Fig. 8 shows results obtained with the engine running on methanol; the specific fuel consumption figures are converted to gasoline equivalent.

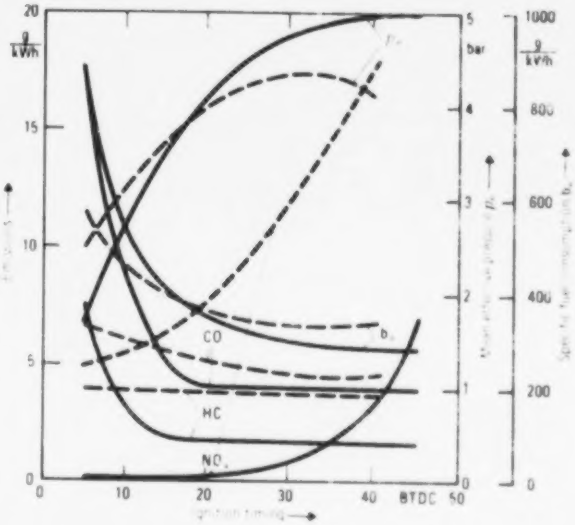

Figure 7 Comparison of operation with gas generator —— λ=1.41 and stock carburettor– – –, λ=1.10 1.6 l VW engine, 2000 rpm

7. Future work and cooperation

Not enough is known about the scaling laws necessary for the enlargement of small test reactors to technical size without loss of gas quality, service life, and conversion rate. The aim of future work must be to improve gas generator components and design and to measure a complete engine map. An optimal zone, determining the set data for the electronic control, will have to be selected from this map.

The Volkswagenwerk is interested in the gas generator for operating an internal combustion engine at low pollutant emissions. For this reason Volkswagenwerk and Siemens have agreed upon cooperative exchange of experience. In this cooperation it is also planned to measure the concentration of polynuclear aromatics and the chemical composition of HC emission in the engine exhaust.

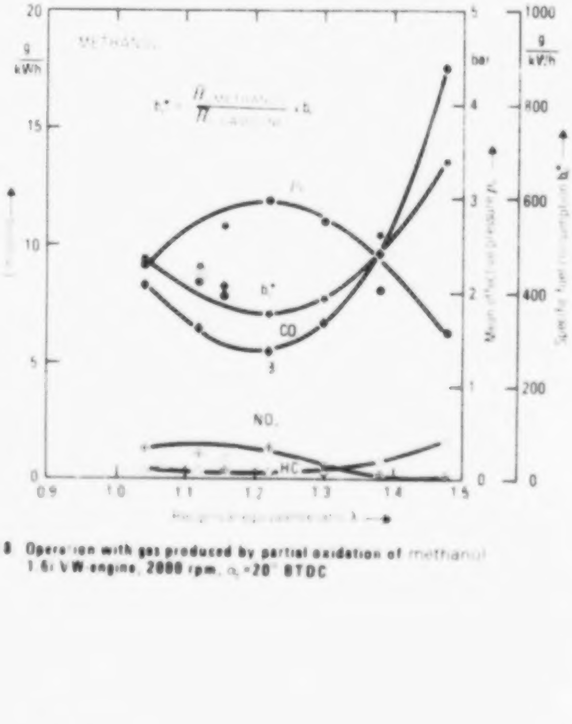

Figure 8 Operation with gas produced by partial oxidation of methanol 1.6 l VW engine, 2000 rpm, α_z =20° BTDC

8. Symbols

λ = reciprocal equivalence ratio
a = cracking number
c_i = molar concentration
p_e = mean effective pressure
b_e = specific fuel consumption
α_z = spark setting
H_u = heat of combustion

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Investigations into the use of the Comprex ® supercharger system on a high-speed diesel car engine

Prof. Dr. E. Eisele
Hiereth, H.
Polz, H.

Following a brief introduction on the operation of the Comprex supercharger, the principal advantages and drawbacks of this system and the experience gained when using this system in conjunction with a 2.2 dm^3 pre-chamber diesel car engine are presented. The major problems which occurred during the development, and the performance and emission figures attained during rig und road tests are discussed.

Après une brève introduction sur le fonctionnement de la suralimentation Comprex, on traite des principaux avantages et inconvénients ainsi que des expériences qui ont été faites avec ce système de suralimentation à un moteur diesel de voiture particulière de 2,2 dm^3 à chambre de précombustion. Sont traités les problèmes majeurs qui se sont présentés au stade de l'étude et les valeurs de performance et d'émission des gaz d'échappement mesurées au banc d'essai et lors d'essais sur route.

Nach einer kurzen Einführung in die Wirkungsweise der Comprex-Aufladung wird über die prinzipiellen Vor- und Nachteile sowie über die Erfahrungen mit diesem Aufladesystem an einem 2.2 dm^3 Vorkammer-PKW-Dieselmotor berichtet. Es werden die bei der Entwicklung aufgetretenen wichtigsten Probleme aufgezeigt und die Leistungs- und Abgaswerte aus Prüfstands- und Fahrversuchsmessungen diskutiert.

Since vehicle engines are being judged more and more on the basis of fuel consumption and exhaust emission characteristics, the diesel engine is becoming increasingly popular today as a drive unit for cars. Compared to the commonly used gasoline engines it has, however, a disadvantage due to the principle on which it works, namely that of low output, which is only approximately 60 % of that of a gasoline engine of the same swept volume. Supercharging is one possible means of overcoming this disadvantage. However, due to the much greater range of engine speeds and the frequent changes in load, supercharging a car diesel engine, as compared to a truck engine, entails a considerably greater amount of development work on the supercharger and the engine. The choice of a suitable supercharger is particularly important here. The pressure-wave supercharger Comprex®, manufactured by BBC, offers favourable characteristics, which are due to its mode of operation and have already proved themselves in truck diesel engines. The next logical step, therefore, was to investigate to what extent the Comprex unit was suitable as a supercharger for car diesel engines.

The standard diesel car engine OM 615 (2.2 litres swept volume) was used as a basic engine for the test (Table 1). It is very important in this connection to point out that only the process was tested, since this engine is designed only for operation as an N.A. engine. The test engine therefore could only be used as such after a specific treatment of the material and special machining of the components, which cannot be done in standard production; also a considerable reduction in the service life of the engine components has to be accepted. This paper deals with the measures adopted and the results obtained in detail.

This necessitates a brief description of the mode of operation of the Comprex supercharging system.

Fig. 1 shows the arrangement of the Comprex unit in relation to the engine. Fig. 2 is a diagram of the pressure waves within the Comprex unit as obtained when unrolling the cell wheel.

The Comprex supercharger system is based on a direct exchange of pulses between the exhaust gas, which is under increased pressure, and the fresh air by means of controlled pressure waves. The individual stages of the process are as follows:

The exhaust gases flow under increased pressure into the cells of a cell wheel. Since these cells are filled with fresh air, the exhaust gases expel this air. Compression is produced by a pressure wave which propagates in the static air at sound velocity and causes an increase in pressure and an acceleration of the boost air. In this way engery from the exhaust gas is directly transmitted to the boost air. When the pressure wave reaches the boost air manifold, the cell must be connected with the boost air manifold. The revolving cell wheel ensures the correct sequence of the cells. To prevent the flow being disturbed by the pressure waves being reflected, the inlet port for the exhaust gas is closed when the cell is turned further; for the same reason the connection with the boost air manifold is also broken one wave sequence later.

The correct choice of the opening point on the exhaust low pressure end enables the exhaust gases, which are still under pressure in the cell, to be expelled completely into the exhaust. The resultant depression wave allows fresh air to enter the cell from the low pressure end. When the cell is completely filled with fresh air, the process is repeated.

This specific supercharging system, just described has certain system-related characteristics, which should also be briefly discussed here. The direct exchange of pulses between the exhaust gas and fresh air causes on the one hand a gain in b.m.e.p., and hence also in torque, at lower engine speeds with a good smoke level. The Comprex responds very quickly when the gas pedal is depressed, i.e. charge air pressure is built up fast, since transmission of pressure from the exhaust gas to the charge air is almost independent of the mechanical acceleration of the cell wheel and the engine. This means that the emission of smoke to be expected when starting or accelerating is very low. On the other hand, the bulk volume of the overall Comprex system is relatively large and its weight is also considerably greater than that of other supercharging systems. Since in addition the arrangement of the gas ducts in relation to the cell wheel cannot be chosen arbitrarily, and since the Comprex unit requires a belt drive, the scope for fitting the unit to the engine is markedly reduced. The volume of scavenging air required by the Comprex entails a considerable increase in the size of the air filter, the intake silencer and exhaust muffler, and the intake and exhaust lines and manifolds. The overall loss in pressure between the filter inlet and the exhaust muffler outlet must not exceed 60 mbars. And finally it should be mentioned that the Comprex systems's cell whell and the pressure waves it reflects produce noises which might prove to be extremely difficult to suppress.

Following this description to the Comprex system and its characterristics, it seems to be necessary to add a few remarks on the adaptation of the engine to the Comprex supercharger. The adaptation between the Comprex unit and the engine on the test rig was carried out by varying the Comprex speed in relation to engine speed using different belt drive ratios, so as to determine the best possible ratio between the two speeds. The geometry and size to the Comprex unit and the gas ducts was fixed according to vehicle requirements in collaboration with BBC. To adapt the combustion system to the supercharger system only a slight reduction in the compression ratio was required.

Since the potentialities of the Comprex supercharger system were also to be investigated, the degree of supercharging was fixed as high as possible; charge air temperature was limited to 170° C, exhaust gas temperature to 830°C.

During the tests difficulties were encountered in stabilizing idling speed and increasing load and engine speed from idle.

A change in the low pressure scavenging inside the Comprex resulted in stable idling conditions. The emissions of smoke at idle speed and the not yet satisfactory ability of the engine to increase load and engine speed clearly show that the test results obtained represent the limit of what can be attained with the present combination of engine and Comprex unit.

A further point was adapting the injection equipment and the engine components to the increased output and stress due to supercharging. The following measures were adopted:

To be able to increase the amount of fuel injected, the diameter of the injection pump element had to be increased from 5.5 to 6 mm. In view of the higher peak pressure within the combustion chamber the nozzle opening pressure had to be increased from 115 to 135 bar. The governor had to be able to provide for a so-called ± variation of the amount of fuel injected depending on the engine speed, and in addition provision had to be made for a possible installation of a boost-pressure-dependent full load stop.

The cylinder head was adjusted, as far as possible, to the increased mechanical stresses by improved cooling.

The pistons had to be adapted to the high pressures prevailing in the supercharged engine by strengthen ing the piston pins. Piston clearance was re-adjusted, and to control the piston temperatures it was necessary to provide for continuous cooling of the piston by spraying it with oil from the crankcase using a spray nozzle.

The crankshaft was subjected to a salt bath nitriding treatment to increase its flexural strength; the crank pin fillets had to be rolled.

When designing the belt drive for the Comprex, allowance had to be made for the high belt speeds on the one hand, and on the other for the steady and transient power requirements for driving the cell wheel. The power requirements of the Comprex rotor under steady-state conditions are only approx. 2 % of the engine output, i.e. 1.5 kW. When the engine is accelerating, however, the belt drive must be able to transmit up to 15 kW to overcome the moment of inertia of the cell wheel. The problem was solved by using a duplex belt drive, as shown in Fig. 3.

The engine results obtained should now be given in detail:

The full load characteristics, i.e. the torque and power output curves, as well as the fuel consumption under these conditions, the smoke density and the exhaust gas temperature are shown in Fig. 4.
Fig. 5 is an overall performance map of the engine.

The exhaust emission levels are shown in the following three diagramms: hydrocarbons in Fig. 6, CO emission in Fig. 7, NO_x emission in Fig. 8.

Fitting the engine with Comprex supercharger into the vehicle presented another problem. Special means of supporting the Comprex unit in the vehicle had to be found, since the Comprex-machine and the silencers used with it are comparatively heavy and vibrate considerably when the vehicle is moving if they are only supported to the exhaust manifold. It should be pointed out, however, that the Comprex unit used was a version of a larger machine which had orginally been developed for 100 - 125 kW truck engines and had been adapted to its present purpose by modifying the cell wheel. Its size and weight therefore do not correspond to that of a potential car version, which partly explains the difficulties encountered with the belt drive and with supporting the unit.

Considerable effort was devoted to reducing the noise produced by the Comprex system. Fig. 9 gives a third octave analyses with and without intake system silencing.

An absorption silencer was fitted on the intake end and completely new, large cross-section absorption mufflers, which are flanged directly onto the Comprex, were developed for the exhaust side. The cross sections of the entire exhaust system had to be adapted to the greater air flow of the Comprex unit.

And finally, a few words on the performance of the vehicle equipped with Comprex supercharger:

The top speed and acceleration in the individual gears are similar to those of the 2-litre gasoline engine. Fig. 10 shows the attainable top speed and the acceleration for the individual ranges as compared to the standard N.A. engine OM 615 and the 2-litre gasoline engine M 115. A comparison of the same engines with respect to fuel consumption and torque characteristics in direct gear is given in Fig. 11.

As far as handling characteristics are concerned the Comprex-equipped engine is similar to the 2-litre gasoline engine. The noise caused by the Comprex unit has been reduced to an acceptable level by carrying out the measures outlined above, but is still clearly audible.

Another feature pecular to the Comprex-equipped engine is that cold starts are carried out using a butterfly in the intake system, by-passing the Comprex unit. When the valve is closed, cold starts present no problem. When the engine fails to start up, however, the Comprex unit is filled with exhaust gas so that whenever a fresh attempt is made to start, heavy white and blue smoke is emitted.

Owing to the sensitivity of the Comprex system to back pressure, CVS tests present problems at the moment, since the specified CVS systems in use by Daimler-Benz builds up back pressures of over 60 mbars. As a result, the recirculation and exhaust characteristics of the Comprex are changed to such an extent that the tests very often cannot be finished. The Comprex chokes !

In conclusion, it can be said that fitting the Comprex unit to a diesel car engine, as well as the rig experiments and road tests carried out with this engine, have revealed the following:

1. Pressure wave supercharging with the Comprex® is in principle also suitable for car engines. The output and torque characteristics attained equalled those of a gasoline engine with about the same swept volume; the emission levels and fuel consumption are more or less the same as those of a N.A. diesel engine.

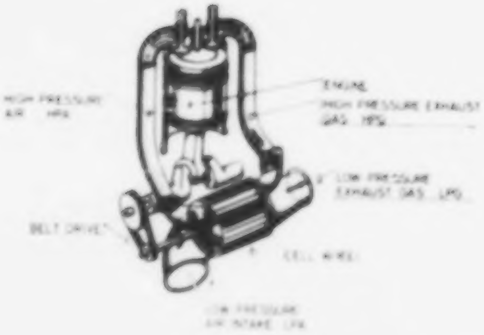
2. The Comprex supercharging system for cars is (unfortunately) only in the initial stages of development as regards space requirements, weight, noise, reliability, and cost.

3. If supercharging is to be applied, the dimensions, design, and development of the basic engine must be reconsidered.

In this study one of several possible means of increasing the output of diesel engines has been examined. The study does not provide an answer to the question as to which is the best means of increasing the output, so more tests will have to be carried out in order to clarify this question, which is extremely important from the point of view of both economy and energy.

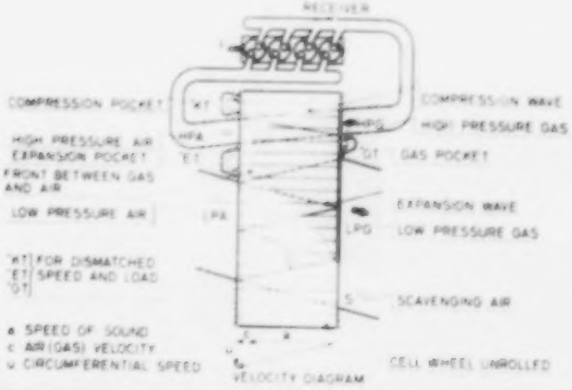
The importance Daimler-Benz attaches to the diesel engine is illustrated by its position in the current model range.

Supercharging changes nothing in the company's opinion of the importance of the diesel engine as expressed therein.


HIGH PRESSURE AIR HPA
ENGINE
HIGH PRESSURE EXHAUST GAS HPG
LOW PRESSURE EXHAUST GAS LPG
BELT DRIVE
CELL WHEEL
LOW PRESSURE AIR INTAKE LPA

PRESSURE WAVE MACHINE COMPREX
SUPERCHARGING APPLICATION

E6LK
Pz 74/001

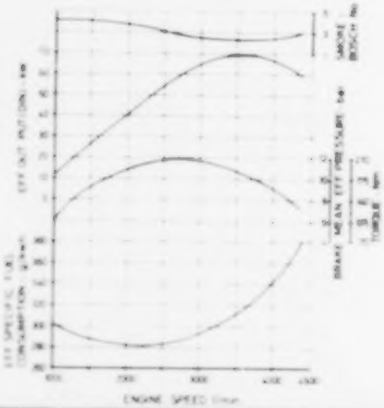


COMPREX-BASIC PRESSURE WAVE PROCESS
WITH BBC-POCKET FOR DISMATCHED SPEED AND LOAD

E6LK
PZ 74/002

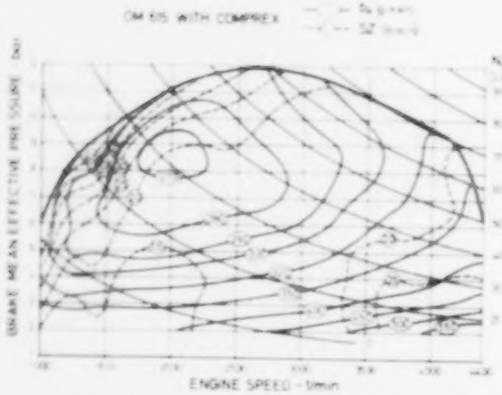
BELT DRIVE OM 615 WITH COMPREX SUPERCHARGER

E6LK
Pz.74/003



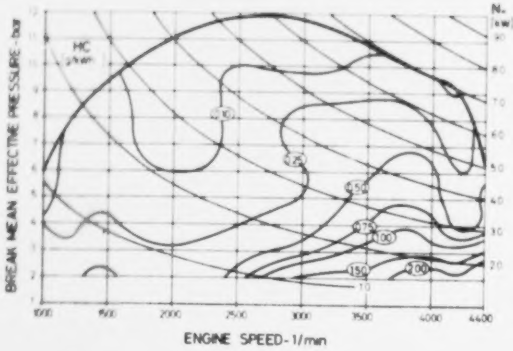
OM 615 WITH COMPREX SUPERCHARGER

E6LK
Pz 74/004



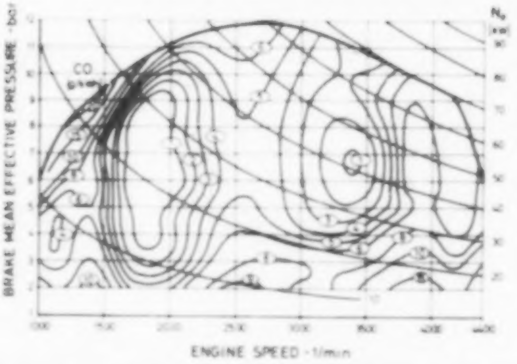
MAP OF SPECIFIC FUEL CONSUMPTION
AND EXHAUST SMOKE

E6LK
Pz 74/005



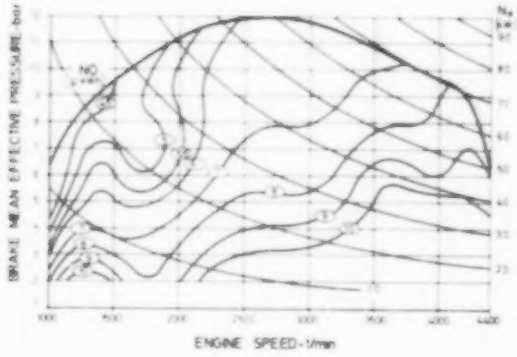
MAP OF HYDROCARBON EMISSIONS
OM 615 WITH COMPREX SUPER CHARGER

E6LK
Pz 74/006



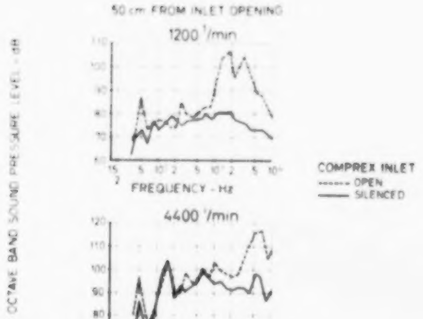
MAP OF CARBONMONOXIDE EMISSIONS
OM 615 WITH COMPREX SUPER CHARGER

EGLK
Pz 74/007



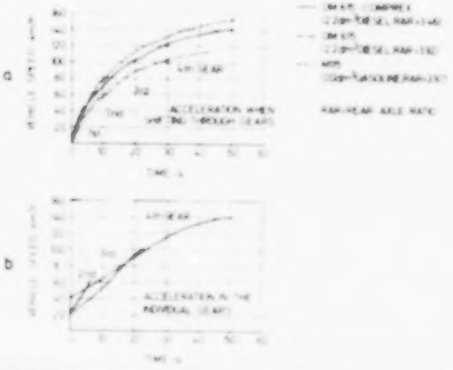
MAP OF NITRIC OXIDE EMISSIONS
OM 615 WITH COMPREX SUPERCHARGER

EGLK
Pz 74/008

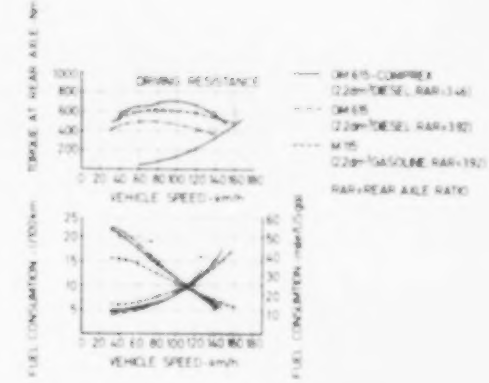


THIRD OCTAVE BAND SPECTRA OF A 2.2 dm³ DIESEL
ENGINE WITH COMPREX SUPERCHARGER

EGLK
Pz 74/009



⅄	**ACCELERATING CAPACITY** LOAD 2 PERSONS	E6LK Pz 74/010



⅄	**DRIVING PERFORMANCE** LOAD 2 PERSONS	E6LK Pz 74/011

ENGINE TECHNICAL DATA

NO OF CYLINDERS	4, IN-LINE
BORE	87mm (3.43 in)
STROKE	92.4mm (3.64 in)
TOTAL DISPLACEMENT	2197 cm³(134 cu in)
COMPRESSION RATIO	19.5:1
COMBUSTION SYSTEM	PRECHAMBER
MAX ENGINE SPEED	4400 1/min
FUEL	DIESEL
INJECTION SYSTEM	MECHANICAL 4-PLUNGER INJECTION PUMP WITH AUTOMATIC TIMING DEVICE

⅄	**TABLE 1**	E6LK Pz 74/Tab1

Appendix to Session 5
Annexe 5 ème Session
Anhang zu Themengruppe 5

Progress reports on the research and development projects promoted by the Federal Minister for Research and Technology

Rapports-bilan relatifs aux projets de recherche et développement encouragés par le Ministre fédéral de la Recherche et de la Technologie

Statusberichte über die vom Bundesminister für Forschung und Technologie geförderten Forschungs- und Entwicklungsvorhaben

As of: August 1974
Situation: Aûot 1974
Stand: August 1974

Verminderung der Schad- und Feststoffemission bei Fahrzeug-Dieselmotoren

Dr.-Ing. H. ZAPF
Maschinenfabrik Augsburg-Nürnberg Aktiengesellschaft
89 Augsburg, Stadtbachstraße 1

The Comprex-charging of Diesel engines aims at two targets:

1. Reduction of NO_x-emission caused by charging
2. Reduction of soot-emission at acceleration caused by the pressure wave principle of this charging method
   Data of noncharged runs and some from the adaption of the Comprex-equipment are already available.

Avec la suralimentation Comprex du moteur Diesel, on vise à atteindre deux objectifs:

1. Réduction des émissions de NO_x par suite de la suralimentation,
2. Diminution des émissions de suie lors de l'accélération par suite du principe des ondes de pression du procédé de suralimentation.
   On dispose de mesurages en service sans suralimentation et de premiers résultats sur l'adaptation du groupe Comprex.

Mit der Comprex-Aufladung des Dieselmotors werden zwei Ziele angestrebt:

1. Verringerung der NO_x-Emission infolge der Aufladung
2. Verringerung der Rußemission beim Beschleunigen infolge des Druckwellenprinzips des Aufladeverfahrens
   Messungen im Saugbetrieb und erste Ergebnisse über die Anpassung des Comprex-Aggregates liegen vor.

Gegenstand der Untersuchungen im Rahmen des seit dem 1. 9. 1973 laufenden Forschungsvorhabens NTO 125 ist in erster Linie, den NO_x-Gehalt und die Rußemission der dieselmotorischen Abgase durch die Aufladung des Motors zu verringern. Die Wirkung der Abgasturbo-Aufladung in Verbindung mit Ladeluftkühlung und Abgasrückführung auf die NO_x-Emission ist bekannt - siehe bspw. /1/, /2/. Ein gravierender Nachteil des abgasturbo-aufgeladenen Motors besteht darin, daß im instationären Betrieb - speziell beim Beschleunigen des Motors - intensive und zeitlich langanhaltende Rußstöße auftreten. Die Ursache liegt in dem durch die Massenträgheit des Turboladerlaufzeuges bedingten Luftmangel bei raschen Last- oder Drehzahländerungen des Motors.

Mit Comprex-Aufladung wird dieser Nachteil des Abgasturboladers vermieden, da infolge des Druckwellenprinzips der Comprex-Aufladung sich der Ladedruck nahezu ohne Zeitverzögerung den neuen Betriebsbedingungen anpaßt.

Die Versuche werden an einem M.A.N.-Fahrzeug-Dieselmotor D 2556 MF durchgeführt.

Technische Daten des Motors:

Zylinderbohrung: $d = 125$ mm
Kolbenhub: $s = 150$ mm
Kompressionsverhältnis
  Saugbetrieb: $\varepsilon = 18$
  aufgeladen: $\varepsilon = 15 \ldots 17$
Nenndrehzahl: $n = 2300$ 1/min
Verbrennungsverfahren: M-Verfahren

Für die Aufladung des Motors sind folgende Aggregate bereitgestellt:

1. Comprex CX 180 PFA 2G (Fa. Brown, Boveri & Cie. AG)
2. Abgasturbolader KKK 4LG 502 (Fa. Kühnle, Kopp & Kausch AG)

Für den Anbau der vorgenannten Auflade-Aggregate wurden die Ladeluft- und Abgasleitungen, der Antrieb und die Befestigung des Comprex-Aggregates am Motor konstruiert und gefertigt. Parallel dazu wurde ein für die vorgesehenen Leistungs-, Abgas- und Beschleunigungsmessungen geeigneter Prüfstand eingerichtet und der Motor aufgebaut.

Zur Überprüfung des Ausgangszustandes des Motors wurde das Betriebskennfeld des Motors im Saugbetrieb aufgenommen. Die Ergebnisse sind in den Bildern 1 und 2 dargestellt.

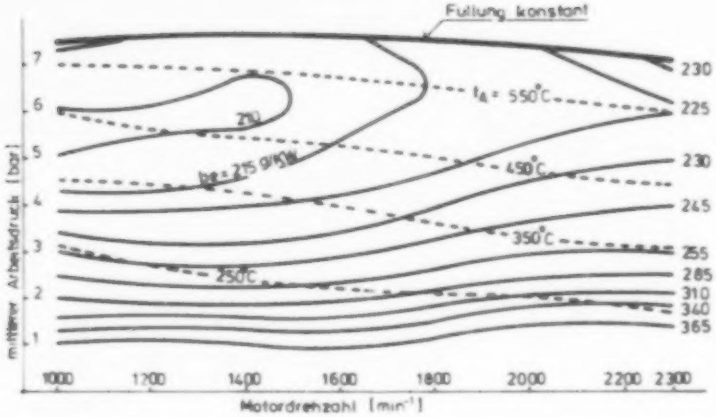


Bild 1: Betriebskennfeld des Motors D 2556 MF (Saugbetrieb) mit spezifischem Brennstoffverbrauch b_e und Abgastemperatur t_A

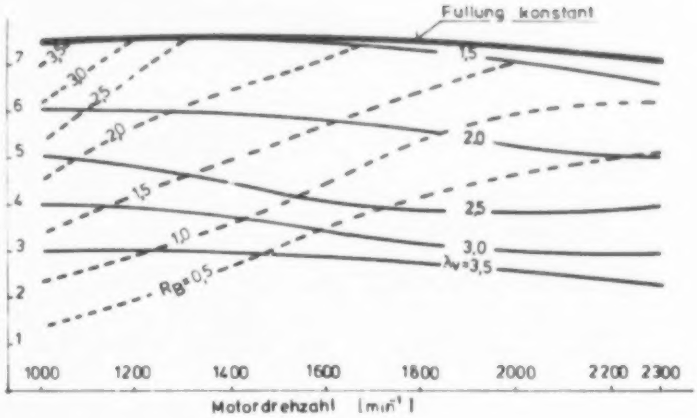


Bild 2: Betriebskennfeld des Motors D 2556 MF (Saugbetrieb) mit Rauchwert nach Bosch RB und Verbrennungsluft-Verhältnis λ_V

In Verbindung mit der Kennfeldaufnahme des Motors wurde im Saugbetrieb zu Vergleichszwecken eine Abgasmessung nach dem 13-Stufen-Zyklus vorgenommen. Dabei ergaben sich folgende Summenwerte:

BSHC = 0,51 g/kW
BSCO = 2,72 g/kW
BSNO = 4,39 g/kW
BSNO$_2$ = 6,74 g/kW
(BSHC + BSNO$_2$) = 7,25 g/kW

Diese Summenwerte sind gerechnet gemäß den Bestimmungen für den USA-13-Stufen-Zyklus für Nutzfahrzeuge mit Dieselmotoren mit einem zulässigen Gesamtgewicht größer 6000 lbs.

Nach Abschluß der Versuche im Saugbetrieb wurde der Motor auf den Betrieb mit Comprex-Aufladung umgerüstet. Das folgende Bild zeigt den Anbau des Auflade-Aggregats an den Motor.

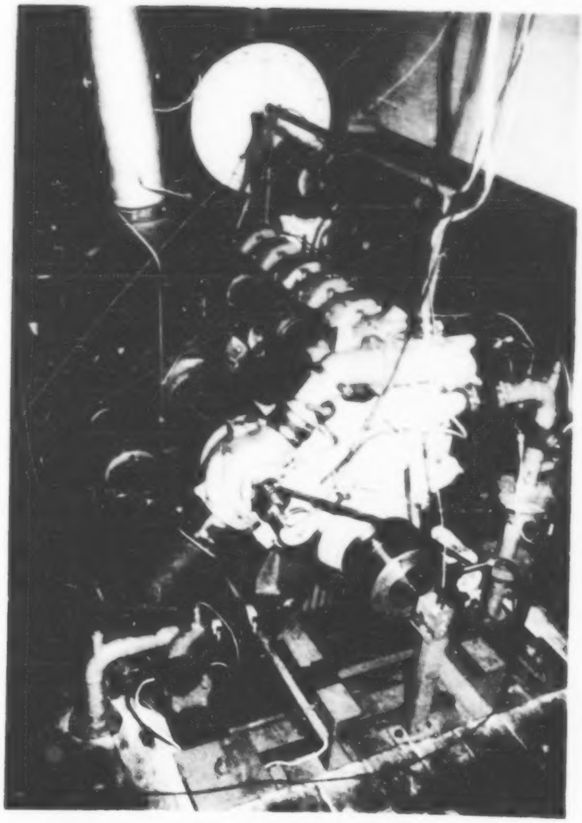


Bild 3: Motor D2556 M-Cx
auf dem Prüfstand

Für die Versuche mit Aufladung sind aus Gründen der Betriebssicherheit vom Motor her folgende Grenzwerte für den maximalen Zylinderdruck $p_{z\,max}$ und die Abgastemperatur $t_{A\,max}$ vor Auflade-Aggregat nicht zu überschreiten:

$$p_{z\,max} = 125 \text{ bar}$$
$$t_{A\,max} = 650\ ^{o}\text{C}$$

Unter Einhaltung dieser Grenzbedingungen konnte bei den ersten Anpassungsversuchen mit dem Comprex-Aggregat ohne Ladeluftkühlung bei Nenndrehzahl eine Leistung von 210 kW gefahren werden. Die Betriebswerte sind noch nicht voll befriedigend, so daß bisher noch keine Abgasmessungen vorgenommen wurden. Im weiteren Verlauf der Versuche ist die Anpassung des Comprex-Aggregats an den Motor zu optimieren. Hierzu gehört auch die Anpassung des Verdichtungsverhältnisses des Motors, des Ladedruckes und des Einspritzbeginnes.

In der Folge sind bezogen auf gleiche Nennleistung des Motors Vergleichsmessungen bezüglich Abgasemission im stationären Betrieb und Rußausstoß beim Beschleunigen zwischen Comprex- und Abgasturbo-Aufladung mit und ohne Ladeluftkühlung und mit und ohne Abgas-Rezirkulation vorgesehen.

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Versuche zur

KRAFTSTOFFVERNEBELUNG

PROF. DR.E.EISELE
BINDER, K.
DREXL, K.
Daimler-Benz AG, Stuttgart

The gas/diesel-oil hybrid system investigated under conditions of simulating pre-fumigation/firing jet operation is one possible means of reducing the soot emission of direkt-injection diesel engines. Improvements with respect to CO, CH and NO_x can be attained using more elaborate control arrangements; this does however, involve higher fuel consumption. Initial experiments with fumigated diesel fuel used as a homogeneous basic quantity have revealed that this type of hybrid system obeys laws which differ from those of a gas/diesel hybrid system.

L'injection de gas-oil dans un gaz différent examiné comme simulation d'une injection de gas-oil dans un mélange vaporisé (air/gas-oil) est une possibilité de réduire l'émission de suie d'un moteur d'injection directe. Quant aux éléments CO, CH et NO_x, il est possible d'obtenir des améliorations avec un plus grand nombre de réglages tout en devant se résigner à accepter une consommation nettement supérieure. Les premiers essais avec du gas-oil vaporisé comme quantité de base homogène montrent que ce genre d'injection est soumis à d'autres lois physiques que l'injection de gas-oil un gaz différent.

Der als Simulation eines Vorvernebelungs-Zündstrahlbetriebs untersuchte Gas/Dieselöl-Mischbetrieb ist eine Möglichkeit, den Ruß eines Direkteinspritzmotors herabzusetzen. Verbesserungen bei CO, CH und NO_x lassen sich mit größerem Regelaufwand unter Inkaufnahme einer Verbrauchsverschlechterung erzielen. Erste Versuche mit vernebeltem Diesel-Kraftstoff als homogene Grundmenge zeigen, daß diese Art Mischbetrieb anderen Gesetzmäßigkeiten unterliegt, als der Gas/Diesel-Mischbetrieb.

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5. Versuchsweiterführung

1. Einleitung

Durch die Erzeugung kleinster Kraftstofftröpfchen in der Gemischbildungsanlage verspricht man sich bei Mehrzylinder-Ottomotoren eine gleichmäßige Belieferung der einzelnen Zylinder, eine Verringerung der zyklischen Schwankungen und eine Verschiebung der fahrbaren λ-Grenze in Richtung mager. Daraus werden ferner Vorteile hinsichtlich Kraftstoffverbrauch und Abgasemission erwartet.

Durch Vorlagern eines bestimmten Grundgemisches in das Saugrohr und Verwenden des direkt eingespritzten Kraftstoffstrahles als Zündquelle könnten beim Dieselmotor die örtlichen Überfettungen am Kraftstoffstrahl und damit evtl. die Rußbildung verringert werden. Bessere Luftausnützung und damit Steigerung der Literleistung sollten sich daraus dann herleiten lassen.

Bei der Suche nach einer für diese beiden motorischen Anwendungsfälle geeigneten Gemischaufbereitungsanlage boten sich zunächst die in anderen Industriezweigen für die Erzeugung kleinster Tröpfchen eingesetzten Ultraschallschwinger an.

Zahlreiche Versuche mit Ultraschallschwingern, die von verschiedenen Herstellern geliefert wurden, zeigten jedoch bald, daß diese Systeme hinsichtlich Standfestigkeit und Vernebelungsleistung noch nicht befriedigen.

Mit einer von DB entwickelten Nebeldüse gelang es bei vergleichbarer Nebelqualität und wesentlich verbesserten Standzeiten größere Vernebelungsleistungen zu erzielen, als dies mit den Ultraschallschwingern möglich war.

Zur Überbrückung der Entwicklungszeit der Nebeldüse wurden an einem Diesel-Einzylinderaggregat mit n-Butan Vorversuche über die Zweckmäßigkeit einer Kraftstoffvorlagerung in das Saugrohr von Dieselmotoren gefahren, wobei die Zündung durch den in der Gegend des Zünd-OT eingespritzten Dieselölstrahls erfolgte.

In diesem Bericht werden der Gas/Diesel-Mischbetrieb, die Funktionsweise der Nebeldüse und Prinzip-Versuche zur Beurteilung der Ausfallneigung von Kraftstoff-Luftgemischen im Ansaugrohr beschrieben.

2. GAS/DIESEL-MISCHBETRIEB

2.1 Wahl des Gases

Je nach dem Aufbereitungsverfahren für den Homogenanteil - Ultraschallvergaser oder Nebeldüse - wird der Dieselkraftstoff nur vernebelt oder aber vielleicht teilweise in kürzere Ketten gecrackt vorliegen. Das zunächst ersatzmäßig zu verwendende Gas sollte daher in seinen Kraftstoffkonstanten dem Dieselkraftstoff möglichst ähnlich sein. Unter den bei atmosphärischen Bedingungen (Zumischung im Saugrohr) gasförmigen Kohlenwasserstoffen hat n-Butan (C_4H_{1o}) die längste Kette und von den Gasen die höchste Cetanzahl, die allerdings erheblich niedriger als die von Dieselöl liegt. Zudem bewirkt die hohe Dichte des n-Butans bei Zumischung ins Saugrohr nur einen vernachlässigbaren Liefergradverlust. Diese Gründe führten zur Verwendung von n-Butan.

2.2 Wahl des Versuchsträgers

Unterteilte Brennräume neigen im Falle hoher Verdichtung beim Gas/Diesel-Mischbetrieb zum Klopfen. Als Versuchsträger wurde daher ein Einzylinder-Aggregat mit direkter Einspritzung und einem Hubraum von o,6 dm^3 gewählt.

2.3 Versuchsparameter

Die Versuche, über die nachfolgend berichtet wird, lassen sich in zwei Parameter-Gruppen einteilen. Konstruktive Parameter sind das Verdichtungsverhältnis, die Einspritzdüse (Lochzahl und Lochdurchmesser), die Brennraumform (Muldenform) und der Einlaßkanal. Bild 1 zeigt links einen Brennraum mit einer tiefen Kolbenmulde und mit einem Drallkanal sowie rechts einen flachen Heron-Brennraum mit einem Einlaß als Füllungskanal. Versuchstechnische Parameter sind das Verhältnis von Gas zu Flüssigkraftstoff, der Spritzbeginn für den Zündstrahl sowie die Regelungsart (Qualitätsregelung = ungedrosselter Betrieb im gesamten Lastbereich bzw. Quantitätsregelung = Ansaugdrosselung in einem Bereich des Luftverhältnisses $\lambda = 1$ bis 1,4 für den gesamten Lastbereich).

2.4 Versuchsergebnisse

2.4.1 Verbrennungsablauf

Oberhalb einer Motordrehzahl von n = 18oo 1/min steigt der Zündverzug mit zunehmender Gaszumischung und Drehzahl an. Bild 2 zeigt die Zündverzugszunahme für den Fall konstanten Spritzbeginns des direkt eingespritzten Zündstrahls. Der starke Anstieg des Zündverzuges bei Gaszugabe ist weniger auf das Verbrennungsverfahren (homogener Ladungsanteil) an sich, als vor allem auf die im Vergleich zum Dieselöl höhere Klopffestigkeit des verwendeten Gases zurückzuführen. Der direkt eingespritzte, als Zündinitial wirkende Kraftstoffstrahl zündet zuerst an seinem verwehten Strahlmantel, wo die Aufbereitung des Kraftstoffes am weitesten fortgeschritten ist. Für dieses Gebiet, in dem sich unmittelbar vor der Entzündung ein Gemisch aus Luft, Gas und verdampftem Dieselöl befindet, gilt eine dem Gas/Diesel Mischungsverhältnis entsprechende "Gemischcetanzahl", die, da das Gas eine niedrige Cetanzahl hat (n-Butan CZ = 12,5), unter der des Diesel-Kraftstoffes liegt. Das Gesamtgemisch wird also mit steigendem Gasanteil zündträger.

Ein wichtiger Aspekt bei der Betrachtung des Verbrennungsablaufes in dem hier ausgeführten Zweistoff-Betrieb ist die nach der Entzündung eintretende schnelle Wärmefreisetzung des homogenen Gas/Luftgemischanteils, die den Brennverlauf deutlich in Richtung Gleichraumverbrennung verschiebt. Die Auswirkungen sind in den Kennlinien Bild 3 für drei aus einer großen Zahl von Varianten herausgegriffene "Brennverfahren" aufgezeigt. Bild 3 a zeigt den reinen Dieselölbetrieb im Vergleich zum Zweistoffbetrieb mit zwei Extremfällen der Parameter-Einstellung in Bild 3 b und 3 c (mit bzw. ohne Ansaugdrall, unterschiedliche Kolbenmuldenform, verschiedene Förderbeginne und Regelungsarten). Dabei sind die Bilder 3 b und 3 c auf eine Mischungscharakteristik des Gas/Diesel-Verhältnisses bezogen, bei der die Zündstrahlmenge über Drehzahl und Last konstant bleibt.

Während bei der Anwendung von Drall (Bild 3 b ganz unten), ein Zündstrahl von 10 mm^3/Spiel ausreicht, um eine sichere Zündung und genügende Flammausbreitung zu erreichen, muß die Zündstrahlmenge im drallfreien Betrieb (Bild 3 c) auf 16 mm^3/Spiel erhöht werden. Durch diese Mischungscharakteristik ändern sich in beiden Fällen die Prozentzahlen für Gas und Dieselöl über Last und Drehzahl derart, daß bei niederer Last ein relativ höherer Dieselölanteil als bei hoher Last die Kraftstoffeingabe bestimmt, wie dies aus dem Heizwertäquivalenten, auf Dieselöl umgerechneten b_{1ges}-Verlauf in Bild 3 b und 3 c unten erkennbar ist.

Die erwähnte , durch den vorgemischten Ladungsanteil bedingte schnelle Wärmefreisetzung ergibt bei frühem Förderbeginn im Zweistoffbetrieb gegenüber dem Dieselölbetrieb - vor allem bei hoher Last mit ihrem entsprechend der Mischungscharakteristik höheren Gasanteil - einen erheblich steileren Druckanstieg $dp/d\alpha$, demzufolge auch höheren Spitzendruck p_{max}, höhere Spitzentemperatur und höhere NO_x-Emission, härteres Laufverhalten (Geräusch), aber andererseits auch besseren Verbrauch b_e und wesentlich günstigeren Rauch SZ. Die Erwartung, durch Vorreaktionen den Druckanstieg zu verkleinern und damit eine Geräuschverbesserung zu erreichen, wird also durch die schnellere Wärmefreisetzung des Homogen-Anteils weitgehend überboten.

Bei spätem Förderbeginn, aber auch, wenn bei höheren Drehzahlen der steigende Zündverzug nicht durch eine Förderbeginn-Früherstellung kompensiert wird, verschleppt sich die Verbrennung durch den zündunwilligeren Gasanteil in den

Expansionstakt, die Abgastemperatur steigt, Spitzendruck und Druckanstieg fallen, der Kraftstoffverbrauch steigt und auch der Rauch verschlechtert sich wieder. Optimale Kompromisse zwischen Druckanstieg, Spitzendruck und NO_x-Emission einerseits bzw. Verbrauch und Rauch andererseits müßten durch entsprechende Förderbeginn-Abstimmung im speziellen Anwendungsfall dann gefunden werden, wobei die schnellere Wärmefreisetzung des Homogen-Anteils ein begrenztes Förderbeginn-Späterstellen evtl. sogar noch ohne merkliche Rauch- und Verbrauchseinbuße zulassen wird. Bild 3 c zeigt Kennlinien für den Fall späten Förderbeginns, jedoch für den Fall Füllungskanal, Heron-Brennraum und Quantitätsregelung.

2.4.2 Abgase

2.4.2.1 Rauch

Zweistoffbetrieb vermindert den Rußausstoß (Schwärzungszahl SZ) nach Bild 3 und Bild 6 erheblich. Sogar ohne Drall ist er besser als bei Dieselölbetrieb mit Drall. Hauptgründe für das rauchgünstigere Vollastverhalten dürften die "flachere" λ-Verteilung im Brennraum und das verwendete Gas sein: Der kleinere Flüssigkeitsstrahl an der Einspritzdüse enthält hier im Gegensatz zum reinen Dieselölbetrieb eine geringere Dieselölmenge und die Restladung besteht aus bereits homogen mit Luft vermischtem Gas gegenüber der reinen Luftladung beim Dieselölbetrieb (die örtlich am Strahl bei $\lambda \leqslant 1$ verbrennende "Fettzonen" - Menge ist also beim Zweistoffverfahren deutlich geringer). Für den auch bei Zweistoffbetrieb noch auftretenden Ruß ist der Dieselölanteil hauptverantwortlich, da Messungen ergaben, daß bei reduzierter Menge im reinen Dieselölbetrieb (also bei Dieselöl-Teillast) und im anschließenden Zweistoffbetrieb mit derselben Dieselölmenge, jedoch plus zusätzlichem Gasanteil (also Zweistoff-Vollast), in etwa gleicher Rauch produziert wird.

Ferner ist auch das verwendete Gas an sich ein Grund für die Rauchverbesserung: Während normalerweise die im Dieselkraftstoff enthaltenen langen Ketten, wie z.B. Cetan, $C_{16}H_{34}$, zu einem relativ größeren C-Betrag gecrackt werden, besteht nun ein gewisser Teil der Kraftstoffmenge aus einer kurzen und vor allem relativ H_2-reicheren und damit C-ärmeren Kette.

2.4.2.2 Stickoxide

Die Bildung von NO_x ist hauptsächlich von λ (O_2-Überschuß), der Höhe der Spitzentemperatur sowie von der Verweilzeit bei der hohen Temperatur abhängig. Bei Vollast bringt die schnelle Wärmefreisetzung des homogen vorgemischten Gas/Luftanteils, vor allem bei einem durch Förderbeginn-Frühersteller gleich gehaltenen Zündzeitpunkt, höhere Spitzentemperaturen.

Durch den homogenen Ladungsanteil des Brennraumes herrschen, wie erwähnt, zudem andere örtliche λ-Verhältnisse als bei reinem Dieselölbetrieb. Der Einspritzstrahl, in dessen Randgebiet NO_x-kritische Bereiche mit $\lambda = 1$ auftreten, ist andererseits beim Zweistoffbetrieb kleiner.

Wegen der niedrigeren Flammenfortpflanzungsgeschwindigkeit bei drallfreier Brennraumfüllung und damit größerem Gleichdruckanteil der Verbrennung hat der Füllungskanal, vor allem im oberen Lastbereich ($\lambda < 2,4$), nach Bild 4 NO_x-Vorteile gegenüber dem Drallkanal, wie dies der Vergleich der Varianten Zweistoffbetrieb mit Qualitätsregelung zeigt.

Förderbeginn-Spätersteilung, die wie bereits erwähnt, bei Zweistoffbetrieb eher möglich ist, da man hier weit genug von der Rauchgrenze entfernt ist, reduziert die NO_x-Emissionen ganz entscheidend.

Obwohl bei der Anwendung von Quantitätsregelung (Drosselklappenregelung für die Luftmenge entsprechend Abschnitt 2.3) nur im λ-Bereich 1 bis 1,4 gefahren wurde, ergibt sich mit Füllungskanal nur bei $\lambda = 1{,}05$, also im theoretischen

NO_x-Maximum, ein höherer spezifischer NO_x-Ausstoß [g/PSh] als bei normalem Dieselölbetrieb, siehe Bild 4.

Für eine evtl. noch nötige weitere Verringerung der NO_x-Emission müßte, wie bekannt, auf externe Abgasrückführung (jedoch mit der Gefahr schlechteren Verbrauches) zurückgegriffen werden oder evtl. müßte interne Abgasrückführung durch entsprechende Wahl der Steuerzeiten angewendet werden.

2.4.2.3 Kohlenmonoxid

Mit sinkender Last, d.h. bei steigendem λ, wenn die Flammenfronten sich dann nicht mehr bis in alle Gebiete des Brennraumes ausbreiten und so ein Teil des homogen gemischten Gases an der Verbrennung nicht mehr teilnimmt, wird in den Randzonen des verbleibenden Verbrennungsgebietes durch unvollständige Verbrennung vor allem des Gasanteils CO gebildet. Die mit der starken Gemischabmagerung einhergehende Abnahme der Reaktionsgeschwindigkeit, d.h. verschleppendes Durchzünden, ist ein weiterer Grund für den Anstieg der CO-Emission . Wie im Bild 4 ersichtlich, steigt der CO-Gehalt aus diesen Gründen bei den drei qualitätsgeregelten Zweistoffvarianten mit kleiner werdender Last, d.h. steigendem λ , auf das Mehrfache des reinen Dieselölbetriebes.

Bei Vollast und damit bei voller Verbrennung der Ladung (d.h. λ = ca. 1,4) sind die CO-Emissionen , und zwar wie die Versuche ergaben unabhängig vom Gas/Diesel-Mischungsverhältnis in etwa gleich denen bei reinem Dieselöl-Betrieb. Mit Drall sind die CO-Emissionen nochmals etwa halb so hoch wie ohne Drall: Bei Anwendung von Drall ist durch den Effekt der thermischen Separierung die Restgemischerfassung zumindest bei Vollast noch einigermaßen gut. Bei Quantitätsregelung wird nach Bild 4 die CO-Emission in genauer Verlängerung der Kurvenverläufe der Qualitätsregelung verkleinert. Hier wird eine echte Verbesserung erzielt - allerdings erkauft durch höheren Verbrauch.

2.4.2.4 Kohlenwasserstoffe

Für die Kohlenwasserstoffe gilt ähnliches wie für die Kohlenmonoxid-Emission. Bei Teillast wird ein Teil der homogen eingebrachten Ladung nicht verbrannt und als C_xH_y in den Auspuff geschoben, besteht jedoch zum großen Teil nur aus photochemisch wenig reaktiven kurzen Kohlenwasserstoffketten. Im Bereich niederer Teillast (hohes λ) bringt die Anwendung von Drallkanälen und Direkteinspritzmulde mit ihrer oben bei der CO-Diskussion schon erwähnten besseren Restgemischerfassung eine bis zu 5 mal kleinere CH-Emission gegenüber Füllungskanälen mit Heron-Brennraum, wie auf Bild 4 gezeigt.

2.4.3 Verdichtungsverhältnis

Verschiedene Verdichtungsverhältnisse wurden erprobt, wobei sich $\varepsilon = 16{,}5$ bei reinem Dieselölbetrieb als Bestvariante gezeigt hat. Bei Zweistoffbetrieb bringt ein niederes Verdichtungsverhältnis ($\varepsilon = 14$ gegenüber $\varepsilon = 16{,}5$) vor allem bei niederen Drehzahlen, tendenzmäßige Vorteile im Verbrauch, Druckanstieg und in der NO_x-Emission.

2.4.4 Folgerungen für den Gas/Diesel-Mischbetrieb

Einige der für einen Motoraufbau prinzipiell möglichen Mischungscharakteristiken des Gas/Dieselöl-Verhältnisses über der Last sind im Bild 5 als Beispiele gegenübergestellt und werden aufgrund der besprochenen Versuchsergebnisse beurteilt.
Bild 5 a zeigt eine Charakteristik Gasanteil/Dieselölanteil = const., wie sie mit herkömmlicher Einspritzpumpe und mengenproportional gekoppelter Gaszufuhr erreichbar wäre. Eine Regel-Charakteristik nach Bild 5 b wäre im Vergleich hierzu einfacher zu realisieren (konstante Zündstrahlmenge, d.h. billige Pumpe ohne Regelung für den Dieselölanteil).

Wie anhand der Versuchsergebnisse in Bild 4 gezeigt wurde, haben Mischungscharakteristiken mit Teillast-Gaszugabe etwa nach Bild 5 a und b bei reiner Qualitätsregelung den Nachteil, daß der homogene Gasanteil im mittleren und unteren Lastgebiet nur unvollständig durchbrennt und somit die CO- und die CH-Werte erheblich über denen des reinen Dieselmotors liegen, und daß außerdem der Kraftstoffverbrauch sich bei Teillast dadurch entsprechend erhöht. Die Charakteristik nach Bild 5 c (einfache Begrenzung der Dieselölmenge im oberen Lastbereich), wäre demnach günstiger, sie nutzt jedoch die Möglichkeiten eines größeren Gasanteils bei oberen Lasten noch nicht weit genug aus. Durch die schnellere Wärmefreisetzung des homogenen Butan-Luftgemisches ergibt sich nämlich bei hoher Last und gutem Ausbrenngrad ein besserer Kraftstoffverbrauch, der durch entsprechende Vergrößerung des Gasanteils noch verstärkt ausgenützt werden könnte. Eine Regelung nach Bild 5 d würde daher vom Verbrennungsverfahren her gesehen den günstigsten Kompromiß bezüglich SZ, b_e und CH-Emission (beeinflußbar noch durch die Wahl des Förderbeginns) versprechen, bedeutet jedoch einen höheren Regelaufwand.

Gas-Dieselöl-Mischbetrieb ist eine Möglichkeit, den Ruß eines Direkteinspritzmotors im oberen Lastbereich deutlich herabzusetzen. Verbesserungen bei den Schadstoffen CO, CH und NO_x lassen sich mit größerem Regelaufwand (Füllungsregelung, evtl. Abgasrückführung) erreichen, allerdings nur unter Inkaufnahme einer beträchtlichen Verschlechterung im Kraftstoffverbrauch. Zweistoffbetrieb im Fahrzeug wäre zudem sicher nur dann sinnvoll, wenn der gasförmige Kraftstoffanteil aus dem Dieselöl in einem bordeigenen Spaltvergaser hergestellt werden könnte, statt ihn in Flaschen transportieren zu müssen.

2.6 Ausblick auf Diesel/Dieselbetrieb

Erste Versuche mit vernebeltem Dieselkraftstoff als homogene Grundmenge zeigen, daß dieser Mischbetrieb anderen Gesetzmäßigkeiten unterliegt, als der Gas-Dieselöl-Mischbetrieb.

3. NEBELDÜSE

3.1 Funktionsweise der Nebeldüse

Die Nebeldüse besteht aus einem elektrisch beheizten Wärmetauscher und einer Zerstäubungsdüse, durch welche der zu vernebelnde flüssige Kraftstoff (Benzin oder Dieselöl) unter Druck strömt und hierbei erhitzt wird. Die Vernebelung erfolgt durch Expansion des erhitzten Kraftstoffes durch die Zerstäubungsdüse. Dabei verdampft der Kraftstoff zunächst in einer Zwischenphase. Bei der anschließenden Rückkondensation entsteht ein Kraftstoffnebel kleinster Tröpfchen.

3.2 Aufbau der Nebeldüse

Den prinzipiellen Aufbau der Nebeldüse zeigt Bild 7. Der elektrisch beheizte Wärmetauscher ist direkt an die Zerstäubungsdüse angebaut. In Spiralnuten des Wärmetauschermantels ist ein Miniatur-Mantelheizleiter verlegt, der zur Verbesserung des Wärmeübergangs mit Thermastix in die Nut eingekittet ist. Als Wärmeisolator nach außen ist auf die gesamte Außenfläche des Wärmetauschers eine Keramikschicht (Al_2O_3) aufgespritzt. Im Inneren des Wärmetauschers ist ein poröser Stab aus Sinter-Bronze eingepreßt. Die glatte Außenfläche dieses Stabes zum Mantel hin und die große Gesamtporenoberfläche, die der Kraftstoff benetzt, ermöglichen einen sehr guten Wärmeübergang zum Kraftstoff. Die Spannung am Heizleiter wird über einen Temperaturfühler geregelt, der die Kraftstofftemperatur vor Eintritt in die Zerstäubungsdüse als Regelgröße erfaßt. Parallel hierzu laufen Versuche mit einem Wärmetauscher der auf der Basis von Whiskern arbeitet.

3.3 Versuchsergebnisse

Bei den ersten Versuchen mit dieser Nebeldüse konnte rein subjektiv die Bildung eines sehr feinen Kraftstoffnebels beobachtet werden. Schwierigkeiten bereitet im Augenblick noch die Temperaturregelung. Des weiteren konnte beobachtet werden, daß sich während des Betriebes der in den Mantel eingepreßte

Stab aus poröser Sinter-Bronze langsam mit einem schwarzglänzenden Lack zusetzt, der sich offensichtlich aus zu hoch erhitztem Kraftstoff aufbaut.

Weitere Schwierigkeiten machte die - allerdings für diesen Verwendungszweck noch nicht optimal ausgelegte Zerstäubungsdüse, deren Nadel zum Klemmen neigt und so zum Ausfall der Nebeldüse führt.

3.4 Weiterentwicklung der Nebeldüse

Die Nebeldüse wird z.Z. hinsichtlich Vereinfachung der Regelung (Selbstregelung durch Verwendung von Kaltleitermaterialien), hinsichtlich der Verbesserung des Wärmeübergangs Heizleiter-Kraftstoff (Direktbeheizung des porösen Sintermaterials) und hinsichtlich Optimierung der Zerstäubungsdüse für diesen speziellen Anwendungsfall der Nebeldüse fortgesetzt.

4. BEURTEILUNG DES KRAFTSTOFF/LUFTGEMISCHES

Die Beurteilung der mittels Vergaser, Ultraschallschwinger und Heizdüse erzeugten Kraftstoffgemische im stationären (nicht-motorischen)Betrieb erfolgte einmal mit einer Ausfallstrecke, zum andern mittels mikroskopischer Untersuchung der Kraftstofftröpfchen.

4.1 Ausfallstrecke

4.1.1 Versuchsaufbau

Bild 8 zeigt den Gesamtaufbau der Ausfallstrecke. Eine Förder pumpe saugt den Kraftstoff aus dem Tank über einen Filter an und führt ihn dem Vernebelungsgerät, d.h. dem Vergaser bzw. dem Ultraschallschwinger zu. Bei der Untersuchung der Nebeldüse werden Hochdruckpumpe und Überdruckventil zwischengeschaltet. Zur Messung der dem Aufbereitungssystem zugeführten Kraftstoffmenge dient ein Meßglas. Die im Motorbetrie als Funktion der Drehzahl auftretenden Strömungsgeschwindigkeiten im Saugrohr des Motors können durch ein in der Preßluftleitung angeordnetes Drosselventil simuliert werden. Die Luftmenge und damit die Strömungsgeschwindigkeit im Saugrohr wird mit einer Luftuhr bestimmt. Die während des Motorbetriebs im Saugrohr auftretenden Schwingungsvorgänge werden vernachlässigt. Das aufbereitete Luft/Kraftstoff-Gemisch wird der mit 2 extremen 9o°- Umlenkungen ausgeführten, horizontal verlaufenden Ausfallstrecke zugeführt. Der in jedem ihrer Längenelemente 1 -15 (s. Bild 9) ausgefallene Kraftstoff wird in Meßgläsern aufgefangen. Je weniger Kraftstoff ausfällt, umso besser ist die Aufbereitung des Luft-Kraftstoff-Gemisches bzw. umso stabiler ist das erzeugte Gemisch gegenüber Niederschlagen bei Strömungsschwankungen und Umlenkungen im Saugrohr. Das nach der Ausfallstrecke verbleibende Luft-Kraftstoff-Gemisch wird durch einen Wasservorhang geleitet und ausgewaschen.

4.1.2 Versuchsdurchführung

Für verschiedene Strömungsgeschwindigkeiten im Saugrohr werden die Ausfallraten über der Ausfallstrecke der mittels Ultraschallschwinger, Nebeldüse und Vergaser aufbereiteten Dieselöl/Luft-Gemische bzw. Benzin/Luft-Gemische ermittelt und verglichen. Da die einzelnen Gemischaufbereitungsanlagen nur als Vesuchsausführung zur Verfügung standen und in ihrer Aufbereitungsleistung unterschiedlich ausgelegt waren, wird bei der Beurteilung der Nebelqualität das Verhältnis Ausfallmenge/Gesamtmenge herangezogen, d.h. bei gleichen durchgesetzten Gesamtmengen jeweils verglichen.

4.1.3 Versuchsergebnisse

In Bild 9 sind die Ausfallraten eines mittels Vergaser, Ultraschallschwinger und mittels Nebeldüse aufbereiteten Benzin-Luft-Gemisches bei einer Strömungsgeschwindigkeit in der Ausfallstrecke von 6o m/s vergleichend dargestellt.

Beim Vergaser sind bis zur Meßstelle 4 bereits über 5o % der eingebrachten Kraftstoffmenge ausgefallen. Unabhängig von den nachfolgenden scharfen Umlenkungen nähert sich die Ausfallrate des Kraftstoffes über der Meßstreckenlänge asymptotisch dem Wert Null. Bei der Nebeldüse wirkt sich zumindest an der Meßstelle 1 die mit steigender Strömungsgeschwindigkeit in der Ausfallstrecke zunehmende Turbulenz auf die Ausfallrate aus. In einem gewissen Streubereich bleibt dann ab der Meßstelle 2 die Ausfallrate über der ganzen Meßstrecke mit Ausnahme der Meßstelle 8 nahezu konstant. Die Ursache der Ausfallspitze an der Meßstelle 8 ist noch nicht völlig geklärt. Versuche zur Klärung dieser Erscheinung laufen z.Z. Offensichtlich hängt die Ausfallrate stark von der Kondensation des Kraftstoffes an der kalten Rohrwand und damit von der Temperatur des Kraftstoffes und der der Rohrwand ab. Diesbezügliche Untersuchungen laufen zur Zeit.

Der nicht optimal arbeitende Ultraschallschwinger "verschluckt" sich häufig, so daß der Kraftstoff teilweise unaufbereitet in die Ausfallstrecke gelangt, was sich in der hohen Niederschlagsrate von 25 % an der Meßstelle 1 ausdrückt. Die Ausfallcharakteristik über der Meßstrecke gleicht der des Vergasers.

Die Aufbereitungsleistung des Ultraschallschwingers nahm während der Versuche infolge Zerstörung der Oberflächenelektroden laufend ab. Nach ca. 3 Std. Betriebsdauer war der Schwinger völlig unbrauchbar. Die Ausfallcharakteristik von mittels Nebeldüse aufbereiteten Dieselgemischen gleicht der auf Bild 9 dargestellten Ausfallcharakteristik für Otto-Kraftstoffe.

4.2 Mikroskopische Untersuchung der Tröpfchengröße

4.2.1 Versuchsaufbau

Die direkte fotografische Aufnahme des in der Luft schwebenden Kraftstoffnebels bereitet aus 2 Gründen Schwierigkeiten:

a) Bei der Aufnahme unter dem Mikroskop ist die Relativbewegung der Tröpfchen zu groß, so daß keine saubere Abbildung möglich ist.

b) Bei Aufnahmen ohne Mikroskop und anschließender Vergrößerung der Bilder fallen die Größenordnung des Filmkorns und der Kraftstofftröpfchen zusammen.

Es wurde deshalb der Weg der indirekten fotografischen Aufnahme über einen Objektträger gewählt. Dabei läßt man den Kraftstoffnebel in eine geeignete Trägerflüssigkeit eintauchen (siehe 4.2.2) und fotografiert die präparierten Nebeltröpfchen unter dem Mikroskop, wobei sich die Tröpfchen als Kreisringe abbilden (vgl. Bild 1o).

Ein in den Strahlengang des Mikroskopes zwischengeschaltetes Interferenzgerät ermöglicht es, die Tröpfchen als Scheiben abzubilden, deren Flächen und Größenverteilung mittels einer Makrovideomateinrichtung ermittelt werden können.

4.2.2 Präparationstechnik

Zur Untersuchung der Nebeltröpfchen unter dem Mikrokop war es notwendig, diese in einer geeigneten Trägerflüssigkeit festzuhalten. Die Auswahl des Trägerstoffes erfolgte unter folgenden Gesichtspunkten:

a) die Tröpfchen dürfen durch das Auftreffen auf der Objektträgerflüssigkeit ihre Form nicht verändern;

b) die Kraftstofftröpfchen sollen in der Trägerflüssigkeit schweben ohne mit dieser zu reagieren;

c) die Tröpfchen dürfen nicht koagulieren.

Unter Berücksichtigung dieser Gesichtspunkte ergab sich als geeignete Objektträgerflüssigkeit eine Mischung aus 1o Teilen Spiritus und 1 Teil Salmiak. Diese Trägerflüssigkeit hat jedoch noch den Nachteil, daß sie sehr rasch verdunstet und nur kurzfristig für die Auswertung zur Verfügung steht. Die Bemühungen gehen nun dahin, das Präparat besser zu konservieren.

4.2.3 Versuchsergebnisse

Da die Erzeugung des Kraftstoffnebels zur Zeit aus Sicherheitsgründen noch nicht unmittelbar in der Nähe des Mikroskops erzeugt werden kann, die Präparate aber - wie oben erwähnt - nur beschränkte Zeit ausgewertet werden können, werden für die weitere Optimierung der Präparations- und Aufnahmetechnik mittels Zerstäubungsdüse erstellte Kraftstoff tröpfchen verwendet.

5. VERSUCHSWEITERFÜHRUNG

Nachdem in stationären Versuchen die Funktionstüchtigkeit der Nebeldüse nachgewiesen, die Qualität des Kraftstoff-Luft-Gemisches im Vergleich zum Vergaser wesentlich verbessert und eine für den Motorbetrieb ausreichende Nebelmenge erzeugt werden konnte, werden die Versuche am Motor fortgesetzt. Dabei soll beim Ottomotor nachgeprüft werden, ob sich durch die wesentlich kleineren Kraftstofftröpfchen eine im Vergleich zum Vergaser gleichmäßigere Gemischverteilung auf die einzelnen Zylinder erreichen läßt.

Eine Verschiebung der Zündgrenze nach höheren λ-Werten hin, d.h. in Richtung magerer und verbesserte Abgasqualität müßte sich hiermit dann erreichen lassen. Zur Überprüfung der Übertragbarkeit der im Gas-Diesel-Mischbetrieb gefundenen Erkenntnisse hinsichtlich Regelcharakteristik, Verbrauch, Leistung und Abgasqualität werden diese Versuche schwerpunktartig mit einem durch Nebeldüse erzeugten Kraftstoffnebel fortgesetzt.

Parallel hierzu sollen geeignete Wärmetauscher für die Nebeldüse entwickelt und deren Regelung optimiert werden.

Auf dem Gebiet der Beurteilung der Nebelqualität werden die Versuche an der Ausfallstrecke fortgesetzt. Dabei soll vor allem der Einfluß der Kraftstofftemperatur auf die Ausfallrate ermittelt werden.

Tröpfchengröße und Größenverteilung werden durch Auswertung der fotografischen Aufnahmen unter dem Mikroskop bestimmt.

Bild 1 : Prinzipskizzen Brennraumform

Bild 2 : Zündverzug bei gleichem Spritzbeginn für verschiedene Gaszumischungen

Bild 3 : Kennlinien für drei Betriebsarten

Bild 4 : Spezifische Abgasemission

Bild 5 : Mischungscharakteristik Gas/Diesel

Bild 6 : Betriebswerte bei Vollast

Bild 7 : Nebeldüse mit Wärmetauscher

Bild 8 : Versuchsaufbau Ausfallstrecke

Bild 9 : Meßergebnisse Ausfallstrecke

Bild 1o : Fotografische Aufnahmen von Dieselöltröpfchen

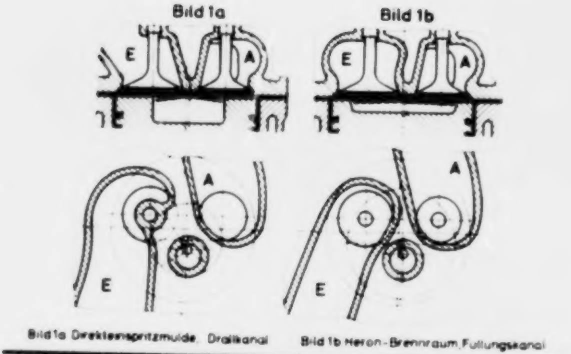
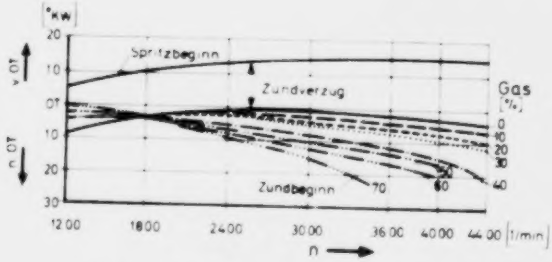


Bild1a Direkteinspritzmulde, Drallkanal   Bild 1b Heron-Brennraum, Füllungskanal

Prinzipskizzen Brennraumformen

0474 E6LK
001 Dre

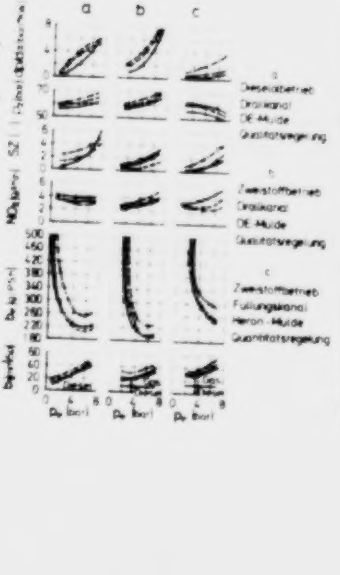
Bild 1



Gesamtmenge b_i = 36 mm³/Spiel
Gasanteil über Heizwert auf Dieselölmenge umgerechnet

Zündverzug für verschiedene
Gas Diesel-Mischverhältnisse

04.74 E6LK
002 Dre

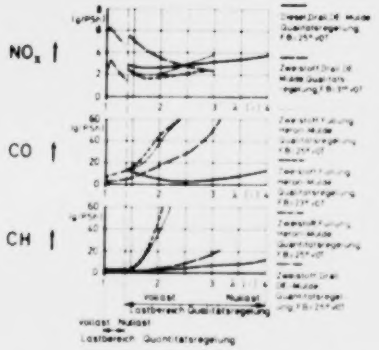


Kennlinien
für drei
versch
Betriebs-
arten

ε = 16,5
— n = 1200 1/min
--- n = 2600 1/min
-·- n = 4000 1/min

04.74 E6LK
003 Dre

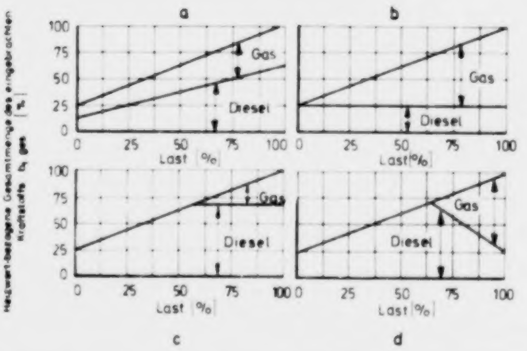
Bild 3



Spez. Abgasemission [g/PSh] über λ
n = 2400 1/min

0474 E6LK
004 Dre

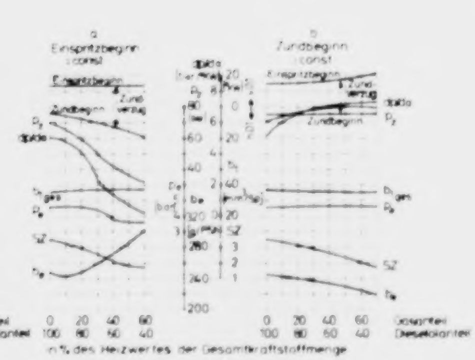
Bild 4



Mischungscharakteristiken Gas Dieselöl

04 74 E6LK
001 Dre

Bild 5

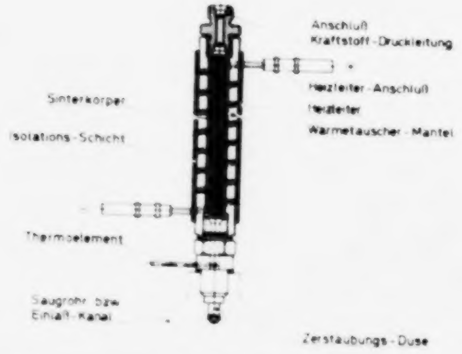


b_{ges} = Heizwert - äquivalente auf Dieselöl umgerechnete Gesamtkraftstoffmenge

Betriebswerte im Vollastpunkt n = 4000 1/min

04 74 E6LK
006 Dre

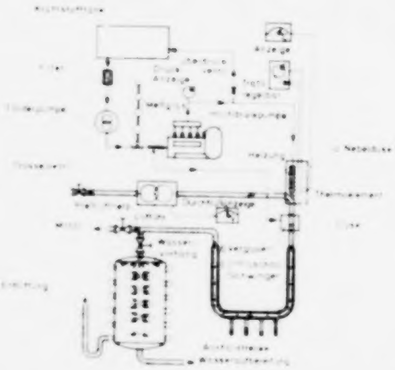
Bild 6



Nebelduse mit Warmetauscher

E6LK
Bi 74/001

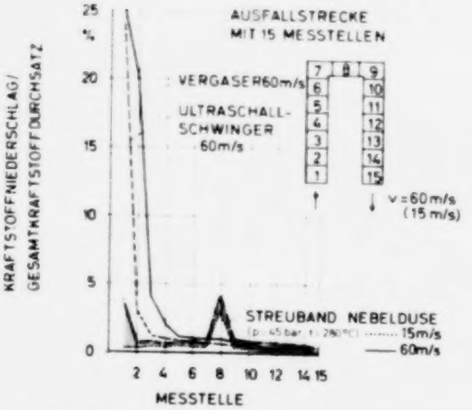
Bild 7



Versuchsaufbau Ausfallstrecke

E6LK
Bi 74/002

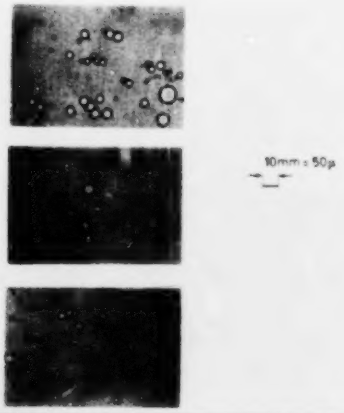
Bild 8



KRAFTSTOFFAUSFALL UBER
DER AUSFALLSTRECKE

E6LK
Bi 74/006

Bild 9



Diesel-Kraftstoff-Tropfchen

E61K
Bi 74/005

Bild 10

[illegible]

Assessment Criteria
# of Advanced Automotive Power Systems

[illegible]

Critères d'évaluation
[illegible]

[illegible]

Beurteilungskriterien
für neuartige Kraftfahrzeugantriebe

Alternative Prime Movers for Future Automobiles

BENO STERNLICHT, Technical Director
Mechanical Technology, Inc., 968 Albany-Shaker Road, Latham,New York 12110
GEORGE M. THUR, Chief, Power Systems Development Branch
U.S. Environmental Protection Agency, Alternative Automotive Power Systems
2929 Plymouth Road, Ann Arbor, Michigan 48105

The paper discusses the automotive issues facing our nation and presents the various options open to us. Test results from a number of different vehicles, using a variety of prime movers, are presented and several conclusions are drawn. The paper points out a strong need for a balanced R&D program which optimizes on a number of conflicting requirements. The spark ignition, internal combustion engine is compared to other potential prime movers and its long-term viability is questioned. A perspective of the automotive propulsion systems is presented that meets the objective of Project Independence.

INTRODUCTION

At the beginning of this century, four prime movers, the Diesel, Otto, Steam-Rankine, and the electric entered the automobile race. In fact, in the early 1900's, there was a time when there were more steam and electric vehicles on the road than Spark Ignition Engines (SIE) (ref. 1). Ford's mass production techniques resulted in low-priced automobiles, and Leland's introduction of the storage battery and electric starter made the SIE highly attractive to the public; thus, it became the leading automotive prime mover. Driveability was later improved by better roads, superhighways, heavier weight cars, and better suspensions. High octane leaded gasoline provided the fuel for the high compression ratio engines of greater horsepower that resulted in higher accelerations and vehicle speeds; unfortunately, all of this was accomplished at the expense of high emissions, and reduced fuel economy.

It is interesting to note that, as we near the turn of this century, the race is being repeated with the same engine contenders, as well as several new entries. While the SIE was the winner for almost a century, it is now being challenged by new national issues (ref. 2). These changing issues are illustrated in Figure 1. Their impact on us is so rapid that the major automobile companies are finding it difficult to cope with them. In the sixties, safety was an important issue. In 1970, the Clean Air Amendments were signed, requiring the automobile to meet the exhaust standards. In 1973, we saw the beginnings of the energy and petroleum crisis. Today, we are already seeing signs of skyrocketing prices for a number of other critical materials, which have limited world supply.

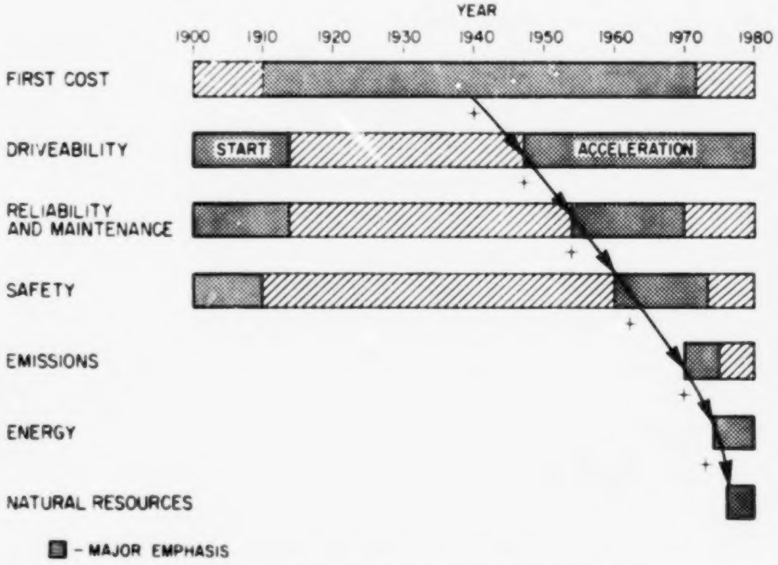


Fig. 1 The Changing Automotive Issues

The automobile and all of the industries that support it represents the largest single segment of our national economy (ref. 2), and has a major impact on our lifestyle. Some of this impact is presented in Table I.

TABLE I AUTOMOBILES REPRESENT

82% of TOTAL U.S. REGISTERED AUTOMOTIVE GROUND TRANSPORTATION VEHICLES

71% of TOTAL U.S. AUTOMOTIVE TRANSPORT FUEL USE

20.5% of TOTAL U.S. ENERGY USE

30.1% of TOTAL U.S. PETROLEUM USE

10% of TOTAL U.S. STEEL AND ALUMINUM USE

5 to 40% of TOTAL U.S. USE OF CRITICAL MATERIALS

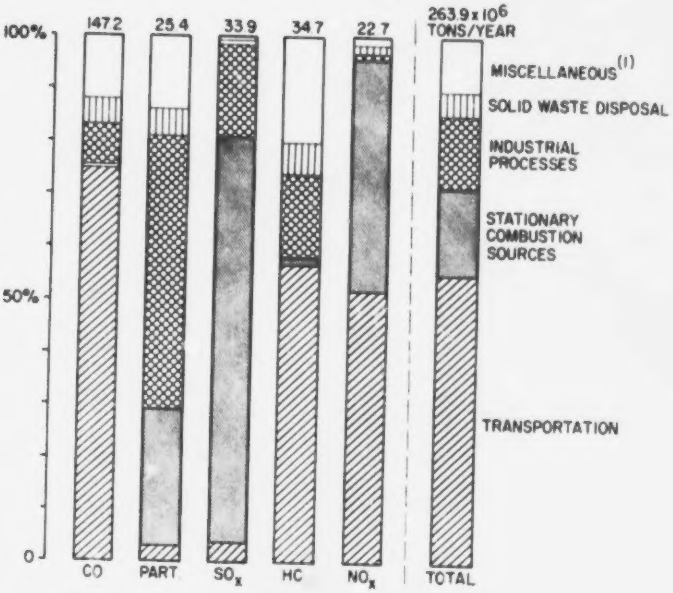
14% of TOTAL U.S. IMPORTS (NEW CARS, ENGINES, FUEL)

27.5% of TOTAL U.S. POLLUTION TOXICITY

Outcries from cities such as Los Angeles, where the automobile contributes 88% of the pollutants and represents a hazard to health, was a major factor in the introduction of the automobile emission standards (ref. 3). Figure 2 shows the breakdown by gases and total pollutants for the transportation sector and other air polluting sources (refs. 4, 5).

More recently, we have become aware of the rapidly increasing prices for the automobiles. Cost of materials has had a major effect on these increases. Several materials, currently among those in short supply, are used in significant quantity in the production of the automobile (ref. 6). These trends will undoubtedly make further increases in automobile prices necessary. Unchecked use will also result in depletion of some of these materials before the end of this century (Figure 3). Further, these represent a significant portion of U.S. mineral imports (Figure 4). This could have a direct impact on our balance of payments (ref. 7).

In order for the electric vehicles to make an "impact" (defined in ref. 3) in the automobile industry, it will be necessary for them to use materials other than zinc, lead, copper, and nickel for batteries and motors. Gas turbines will also have to use materials other than high nickel steel for high temperature turbine wheels. New materials will also have to be developed which are plentiful, inexpensive, and have satisfactory or improved properties to those currently used.



(1) PRIMARILY FOREST FIRES, AGRICULTURAL BURNING
DATA SOURCE: COUNCIL ON ENVIRONMENTAL QUALITY, AUGUST 1972.

Fig. 2 Atmospheric Pollutants (Weight Basis)
U.S. - 1970

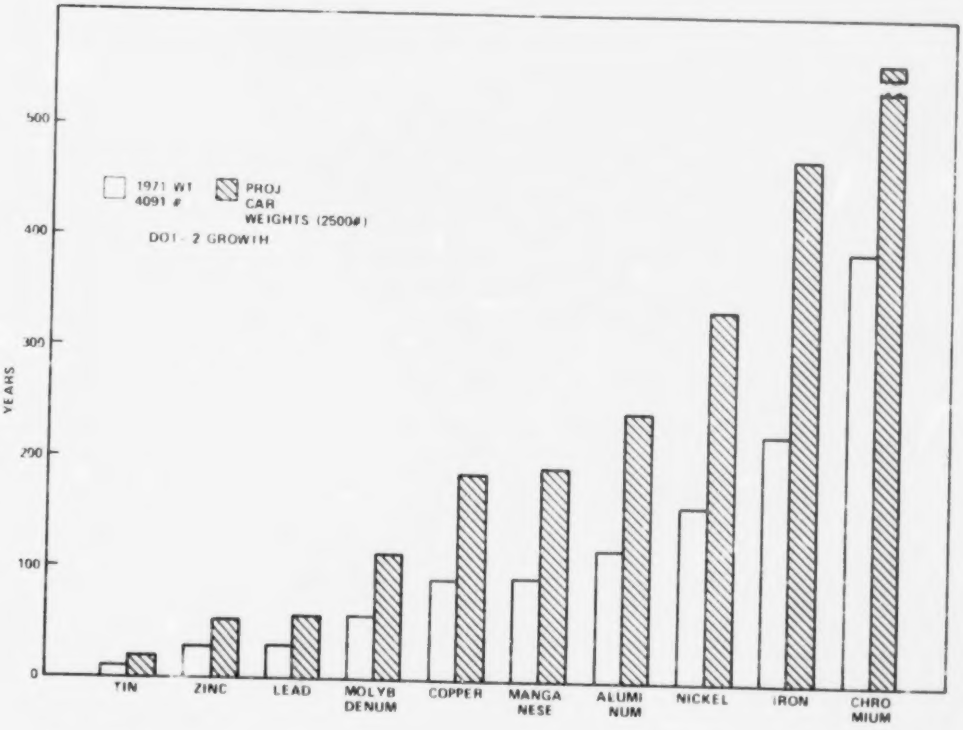


Fig. 3 Years to Depletion of U.S. Auto Reserve - Materials

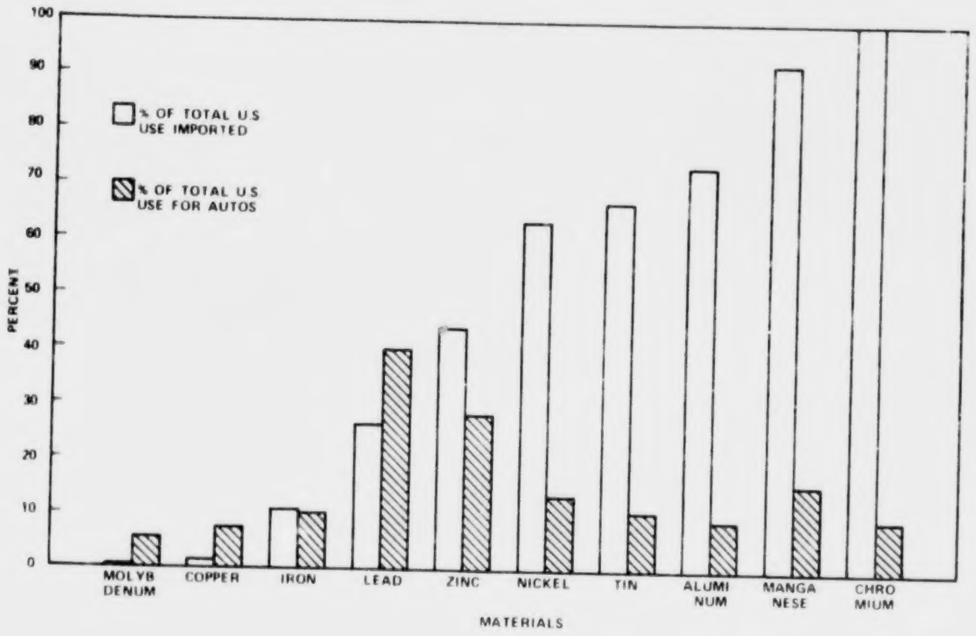


Fig. 4 Natural Resources - Auto Use and Imports (1970)

The above observations represent national issues of major proportions and, therefore, require concentrated R&D effort and close partnership between industry, government, and public. We cannot afford to make too many mistakes, for the time for "impact" of a new automobile engine is long (~ 15 years), and the cost is very high. By the year 2000, it is likely that only two new prime movers may reach the market place (ref. 3). It, therefore, should be recognized that the prime goal in this R&D effort must be CONSERVATION OF ENERGY AND NATURAL RESOURCES IN ENVIRONMENTALLY AND ECONOMICALLY SOUND WAYS. The automobile system, as defined in Table II, represents considerably more than just the engine. All the factors listed will have to be considered in order to come up with a BALANCED PROGRAM (Figure 5). The factors are very complex, highly interactive, and often conflicting. It is therefore very important that we understand the effect of each parameter and how it is influenced by the other factors. It is not surprising that the wrong conclusions have often been drawn, based on either poor understanding of the interactions, or an acute scarcity of accurate, comparative test data.

On a short-term basis, major gains in fuel economy and natural resources can be achieved only with the use of lightweight vehicles, low horsepower engines minimum use of accessories, automatic transmissions that are well-matched with the engines, radial tires, low drag coefficient body styles, and a limit on maximum road speed. These changes will, of course, affect our driving habits, safety and lifestyle. We will not be able to accelerate rapidly in order to pass a car, or get to our destination as rapidly as we would like to. But these changes may be necessary. On an intermediate basis, we should be able to develop and impact the market place with infinitely variable transmissions (IVT), more efficiently integrated accessories, energy recovery systems, turbocharged, compound and binary engines, etc. These will further improve automobile fuel economy and also meet some of the secondary goals (Table II). Only on a long-term basis can we hope to develop and impact the market place with new, very high performance prime movers that will also be able to use new energy sources. The race is on and the challenge is here. We must make sure that we win this race, for the stakes are very high. They affect the future of our whole national economy.

TABLE II AUTOMOBILE SYSTEM

FACTORS	CHARACTERISTICS	GOALS
Vehicle	Inertia Weight Drag Characteristics Tire-Road Friction	Primary Goals ENERGY CONSERVATION Secondary Goals • Environmentally Sound • Minimum Life Cycle Cost • Safe and Responsive to Driver Habits
Engine	Steady State Torque-Speed Efficiency Characteristics Transient Torque-Speed Efficiency Characteristics	
Transmissions	Steady State Torque-Speed Efficiency Characteristics Transient Torque-Speed Efficiency Characteristics Engine-Transmission Matching (Tracking Capability)	
Energy Storage	Energy Storage Power Density	
Accessories	Power Demand Integration with Engine and Transmission	
Driveability	Starting Time Acceleration Deceleration — Non Regenerative Regenerative Stopping Time Smoothness of Operation	
Driving Cycle	Time for each operating condition Number of starts Acceleration Deceleration	

The paper tries to be factual, provide a better understanding of this important subject, and stimulate the reader with new ideas. For completeness, the paper is divided into several sections. The first of these presents test results obtained for a number of vehicles that were tested by EPA over the past several years. These tests were conducted in one laboratory, under identical operating conditions - Federal Driving Cycle (FDC)- using the same well-calibrated instrumentation and experienced personnel. Even if someone wishes to question the accuracy of the laboratory vs. field testing or the applicability of the FDC, one cannot question the validity of the relative comparison that these results represent. A number of very important lessons have been learned from these test results; they are pointed out in the section dealing with the test results. These observations should, of course, provide guidance for an effective, balanced, developmental program (ref. 8).

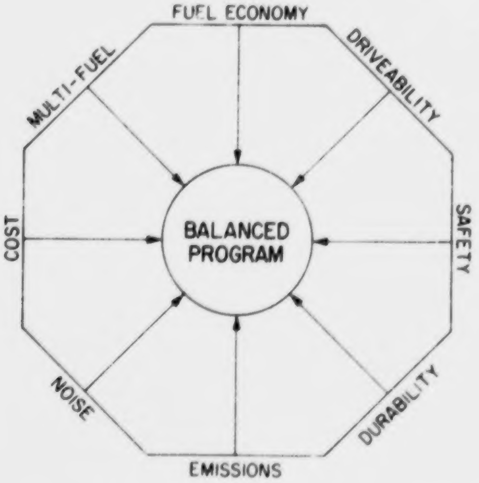


Fig. 5 Factors in a Balanced Program

The paper discusses a number of alternatives open to us; they include the use of new fuels and energy storage devices, both electrical and mechanical. The paper concludes with a broad program outline and presents an overall perspective on how this program can influence PROJECT INDEPENDENCE.

TEST RESULTS

Of all the changing criteria being imposed on today's automobile, the one that has had the most impact from the standpoint of upgrading technology and inspiring alternative propulsion system development has been the original stringent U.S. 1976 emission standards. These emission standards are:

HC	.41 gm/mi.
CO	3.4 gm/mi.
NO_x	.4 gm/mi.

Although the above standard has been deferred until model year 1978 (and may even be deferred further), its introduction as law via the Clean Air Act Amendments of 1970 has already caused major changes in the conventional car and stimulated new developments on alternative systems. Many of these systems have been installed in vehicles and tested for emissions and fuel economy. The EPA Testing Laboratories in Ann Arbor, Michigan, have been the focal point in the accumulation of vehicle test data. The test results, therefore, reflect uniformity in the method of testing, instrumentation, dynamometers used, test drivers' driving habits, etc. Sufficient conventional and alternative propulsion systems have been tested during the past years to allow a better understanding of the various relationships between fuel economy and engine performance versus various emission levels, and the relationship of engine displacement, vehicle weight, axle ratios, etc. versus emissions and fuel economy. The accumulation of such test data reflects a knowledge, heretofore not available to anyone outside the auto industry.

TABLE III EPA'S VEHICLE TEST RESULTS(1)

							GM/MI FDC EMISSIONS			FDC		MODEL YEAR 1974
CARS TESTED	ENGINE TYPE	DATE TESTED	HP	CID	TEST WEIGHT	FTP	HC	CO	NOX	FUEL ECONOMY	FUEL	AVERAGE MPG IN WT. CLASS
1. Spark Ignition Eng.												
VW	ICE	5/74	60	97	2750	75	2.2	12.00	2.8	22.0	Gasoline	17.7
* Ford Gran Torino	ICE	5/73	64	351	4000	75	.27	2.18	.13	9.21	Gasoline	11.6
2. Rotary												
Mazda R100	Wankel	9/72	-	60	2750	75	6.13	33.18	1.25	14.6	Gasoline	21.0
Mazda RX3	Wankel	2/73	90	210	2750	75	.21	1.79	.99	12.4	Gasoline	17.7
Mazda RX4	Wankel	2/73	110	240	3000	75	.31	2.50	1.46	11.9	Gasoline	14.8
3. Stratified Charge												
Honda Civic	CVCC	12/72	65	119	2000	75	.21	1.96	.81	21.6	Gasoline	24.1
* M 151	TCCS	8/72	64	141	2750	72	.3	.67	.34	15.6	Kerosene	17.7
Capri	PROCO	-	73	141	2750	75	.15	.51	1.38	23.3	Gasoline	17.7
Impala	CVCC	10/73	160	350	5000	75	.4	3.33	1.72	10.7	Gasoline	9.1
4. Diesel												
Opel	Diesel	3/73	68	126	3000	75	.40	1.16	1.34	23.8	Diesel	14.8
Peugeot	Diesel	3/73	65	129	3000	75	3.11	3.42	1.07	25.2	Diesel	14.8
Mercedes	Diesel	3/73	65	134	3500	75	.34	1.42	1.43	23.6	Diesel	13.7
5. Rankine System												
* Carter VW	Steam	5/74	-	35	2750	75	.4	1.09	.33	14.9	Kero/Indolene	17.7
General Motors	Steam	4/71	-	-	3500	72	1.15	2.33	1.76	7.1	Kerosene	13.7
General Motors	Steam	4/71	-	-	5500	72	3.29	14.77	2.09	3.1	Kerosene	8.2
6. Gas Turbine												
Williams VW	Gas Turbine	5/71	80	-	2500	72	.34	4.50	1.81	8.5	Gasoline	18.7
Williams AM	Gas Turbine	3/72	80	-	3500	72	.23	7.92	2.64	7.5	Gasoline	13.7
Chrysler	Gas Turbine	8/74	150	-	4300	75	.52	4.78	1.87	8.5	Diesel	9.6

* Vehicles meeting the 1976 Emissions Standards

Table III represents an accumulation of test results dating back to 1968, when the first vehicles were tested on dynamometer rolls at the Willow Run Facilities in Michigan using the constant volume sampling system (CVS) for the measurement of HC, CO, and NO_x. The data was measured on vehicles that were provided by manufacturers for emission certification and also on vehicles that were provided from industry and government development programs. Although electric and hybrid vehicles were tested in the EPA Test Lab, their data is not shown in this table due to some anomolies with the test results or lack of correlation to a specific baseline. To date, no Stirling system has been installed into a vehicle, although the Ford Motor Company, with Philips Co. of Holland, is planning a test in 1975. It should also be pointed out that this table reflects technology as of the date the vehicle was tested. Further, improvements in fuel economy, emissions and engine performance may be possible to different degrees for each of the systems shown. The Table provides important information from the standpoint of predicting trends.

The results are tabulated by various engine types, and several key parameters are compared. Note the effect of weight and horsepower on tested fuel economy and NO_x. It is important to point out that traction is actually more important than horsepower, but this data is very seldom available. For this reason, results of the gas turbine engine cannot be easily compared to the other positive displacement engines. Note also that most of the engines tested had better fuel economy than the average 1974 SIE of the same weight class.

Of all the vehicles tested, only three concepts have met the original emission standards. These are marked with a star in Table III. None met the durability requirement of meeting the emission standards for 50,000 miles.

1. The Spark Ignition Engine was a 1972 Ford Gran Torino. The emission control system included:

a) One Englehard PTX-4237 catalyst per cylinder bank.

b) One Gould NO_x catalytic reactor (composed of nickel/copper on a metallic monolith) per cylinder bank.

c) Quick warm-up provisions which included 10° spark retard during the first 45 seconds of operation, and exhaust port air injection during the first two minutes of operation.

NO_x levels, measured during tests on this vehicle, were very low, considering that the engine utilized no EGR system. The fuel economy of the test car was on the low end of fuel economies for the 1974 model weight class.

2. The Stratified Charge Engine was installed in an Army M-151 1/4 ton truck (Jeep), with a four-speed manual transmission. It had a 141 CID water-cooled, four cylinder engine, using the Texaco stratified charge concept with multifuel combustion capability (TCCS). The emission control system included:

a) A cooled two-rate EGR system used to control oxides of nitrogen, a high rate used for part load operation and a low rate for high load operation. The EGR system also incorporated a particulate trap and a mixing device.

b) A platinum loaded close-coupled catalytic reactor whose design incorporated a tangental swirling action of the exhaust to provide for turbulent mixing. In addition, two reactors of a through-flow design were employed, one loaded with platinum, one with copper chromite. All catalytic reactors were designed and fabricated by Texaco.

c) Intake air throttling at idle and light load was used to increase exhaust temperature during these modes of operation.

The test results indicate that:

- The engine and emission control system required major maintenance during the 50,000 miles of durability testing in order to meet the statutory 1976 emission standards.

- The vehicle demonstrated poor driveability and low power throughout this testing.
- Extensive use of catalytic reactors was required in Texaco's emission control system.

3. The Carter Rankine Cycle System was installed in a Volkswagen "Squareback" station wagon. The expander is a four cylinder radial, single acting uniflow engine without crossheads and is designed to operate on 2000 psi steam pressure and 1000°F with a maximum driveshaft speed of 5000 rpm. The boiler is of a variable pressure monotube type, fired by a modulating burner utilizing a modified spinning cup fuel atomizer. Fuel used was a blend of 50% (by volume) Indolene and 50% kerosene. The complete steam system in its present prototype configuration weighs approximately 20 pounds more than the original internal combustion engine. The standard VW four-speed trans-axle transmission was used, with the steam system occupying the normal engine compartment except for a small ram-air condenser located at the front of the vehicle, and a small forced-air condenser located at the rear of the vehicle. The dry weight of the car is 2470 pounds. Vehicle test instrumentation was neatly packaged in the vehicle dashboard. Externally, the vehicle closely resembled the original vehicle.

The test results showed that the Carter Rankine Steam System could meet the original 1976 statutory emission levels without the use of any exhaust aftertreatment. The vehicle performed well during the EPA tests.

Each of the three (3) systems that met the statutory emission levels were different in the approach used to meet the NO_x levels. The SIE with the Oxidizing and Reducing catalyst used no EGR and the clean-up was solely by aftertreatment. It operated at combustion temperature that did not impact significantly on either fuel economy or engine performance.

The combustion process in a fuel-injected Stratified Charge engine is in some ways similar to that in a prechamber or swirl chamber diesel. The air supply is not throttled, except at idle, so that an excess of air is present throughout the load range; however, the fuel-air mixture is heterogeneous, and combustion takes place initially in a fuel-rich zone. As a consequence of the excess of air normally present, Stratified Charge engines tend to be inherently low emitters of HC and CO, although not to the extent that a diesel is, and catalytic treatment is required to bring the level down to the original 1976 emission levels. Like the diesel, NO_x levels are low enough without using EGR or timing retard to meet a NO_x level of 2 gm/mi. Meeting the 0.4 gm/mi. NO_x levels with the Stratified Charge engine can be rather costly in terms of additional fuel consumption and reduction in W.O.T. maximum traction for a given engine displacement. Figure 6 (ref. 9) shows the reduction in fuel economy for the TCCS Turbocharge Engine with various degrees of emission control and retard timing. Table IV gives details on the various parameters that were changed during the test and the recorded emissions over the FDC. Figure 6 also shows the impact of NO_x on fuel economy for other stratified charge and spark ignition engines tested and adjusted to a 2750 lb. inertia test weight.

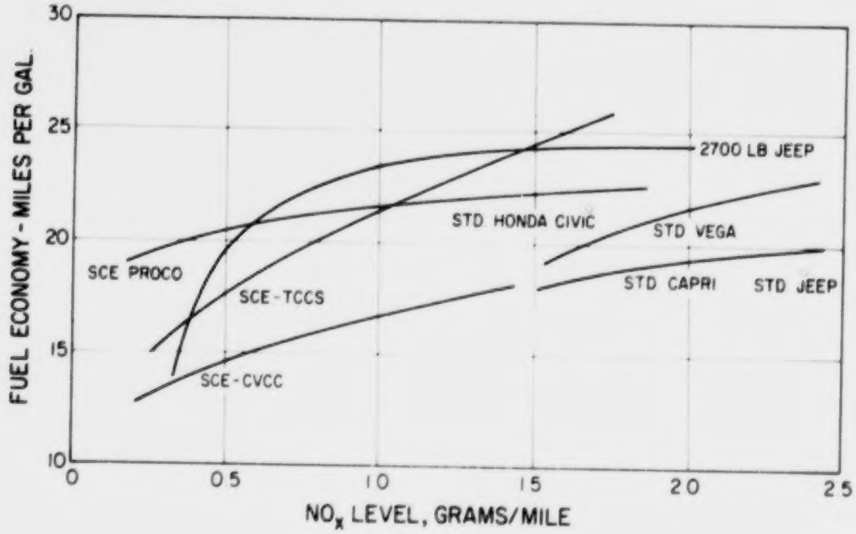


Fig. 6 Fuel Economy, NO_x and Stratified Charge Engines (1975 FTP, 2750 lb. Inertia, Manual Transmissions)

TABLE IV TCCS TURBOCHARGED ENGINE, EMISSIONS AND PERFORMANCE COMPARISON WITH VARIOUS DEGREES OF EMISSION CONTROL - FUEL - GASOLINE

EMISSIONS - GR/MI			MAX. W.O.T. TRACTION-LBS	CYCLE FUEL ECONOMY-MPG	FUEL ECONOMY PENALTY	
HC	CO	NOX			PER CONTROL	TOTAL
TCCS Turbocharged Prototype Engine - No Controls						
3.70	7.96	4.27	330	-	-	-
TCCS Turbocharged Demonstration Engine - No Controls						
3.13	7.00	1.46	310	24.33	0	0
TCCS Turbocharged Demonstration Engine 8° Combustion Retard						
3.24	6.43	1.29	305	22.35	8.1	8.1
TCCS Turbocharged Demonstration Engine 8° Comb. Retrd. + 11% Max. E.G.R.						
3.60	6.69	0.84	300	20.48	8.3	15.8
TCCS Turbocharged Demonstration Engine 8° Comb. Retrd. + 16% Max. E.G.R. + 2 Catalysts						
0.22	1.29	0.66	290	19.43	5.1	20.1
TCCS Turbocharged Demonstration Engine-Full Controls 13° Comb. Retrd. + 22% Max. E.G.R. + 2 Catalysts						
0.36	1.41	0.35	215	16.20	16.6	33.4

In spite of the radical drop in fuel economy for the Stratified Charge TCCS system when meeting the 0.4 gm/mi. NO_x, the economy of the fully controlled Stratified Charge TCCS system could be considered comparable or approximately 10% lower than the average economy in that weight class. The major factor that must be considered is the engine performance penalty. A 30% increase in engine displacement may be necessary to restore the necessary traction power required to meet vehicle road requirements. This displacement increase will cause a further decrease in fuel economy. Figure 7 shows the reduction in W.O.T. Maximum Traction of the TCCS Stratified Charge. For different emission levels, similar characteristics can be noted in the conventional SIE when EGR and retarded timing is used to control NO_x emissions. This illustrates the conflict between two requirements - high fuel economy and low emissions. In general, Internal Combustion Engines (ICE) using intermittent combustion, will exhibit this conflict.

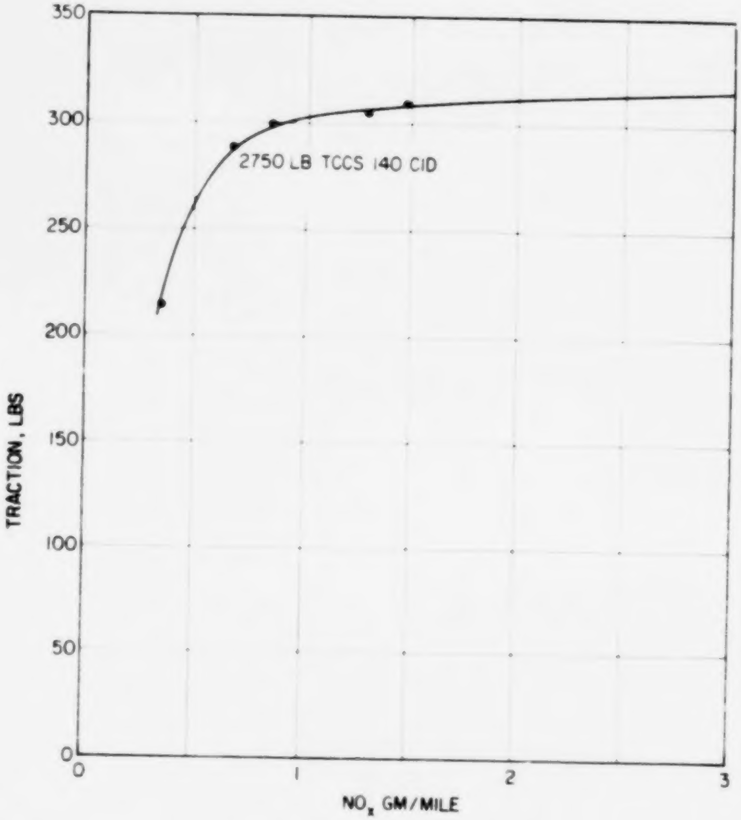


Fig. 7 Traction vs. NO_x

Applicable techniques for reducing NO_x emissions for the diesels include minor modifications of combustion chamber and injector design, retarded variable timing, and EGR. The final results of these techniques on fuel economy and engine performance will be similar to those encountered by the Stratified Charge.

The Rankine Steam System requires no exhaust aftertreatment, since a number of combustion design techniques are available that are not available for the IC system. The Rankine system combustor operates continuously using a modulating control system that maintains the proper fuel rate versus load. The combustion occurs very nearly at ambient pressures; since the working fluid temperature of the Rankine cycle is much lower than the combustion temperature, quenching techniques can be used to suppress NO_x generation rates and dwell times can be reduced by proper design and placement of boiler cold surfaces. Thus, with internal combustion, fuel economy and engine performance are decoupled from emissions. This is highly desirable, for each problem can be treated independently of the other. Due to the larger mass of a Rankine burner/vapor generator HC and CO spikes on start up and during some transient conditions tend to be the major design concerns for the Rankine burner designer.

At a NO_x level of 0.4 gm/mi., the fuel economy of the Stratified Charge and the Rankine system are comparable and approximately 10% better than the SIE with oxidizing and reducing catalyst when adjusted to the same test weight. When adjusted for performance, the Stratified Charge will be lower than the Rankine and SIE in fuel economy.

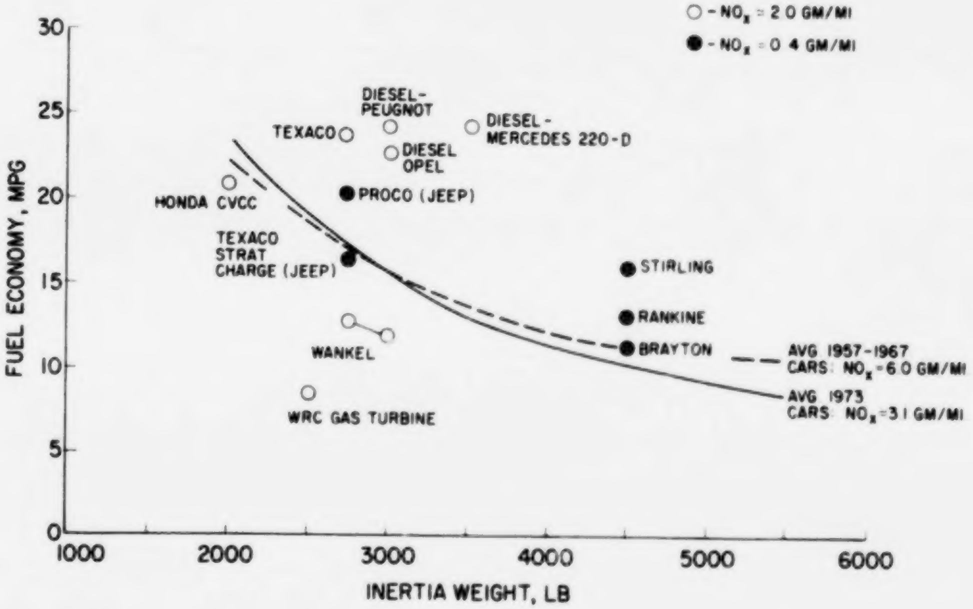


Fig. 8 Fuel Economy Over the Federal Driving Cycle

Figure 8 shows fuel economy plotted vs. inertia weight for various engine types. This figure is presented to point out trends only. It shows that several engine types in a given weight class have better fuel economy than the 1973 average. The 4500 lb. vehicles are all in various stages of development. The

Diesel and some of the Stratified Charge engines are in low production. The effect of time to accelerate up to 60 mph on fuel economy for the FDC is shown in Figure 9 (ref. 10).

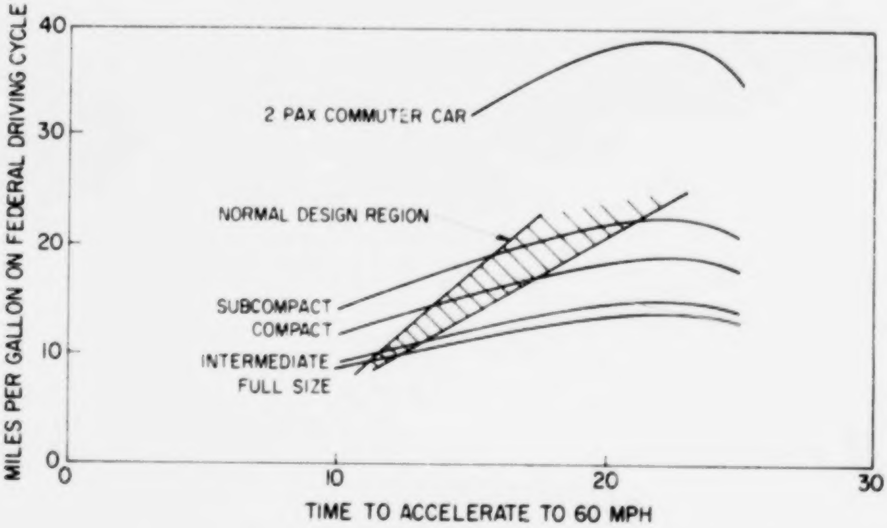


Fig. 9 Relationship between Fuel Consumption and Acceleration

The curves cover several classes of automobiles. These classes are related to weight and size of the vehicles. Note the major gains in fuel economy (3:1) that are possible between the full or intermediate size vehicle and the 2PAX Commuter Car. It was pointed out earlier that traction has major effects on fuel economy, acceleration, and NO_x. Traction is dependent on the engine performance map and the ability of the transmission to most efficiently match the optimum engine performance for the various road load conditions. In Figure 10, the effect of Infinitely Variable Transmission (IVT) over three-speed automatics is illustrated. The IVT falls into two major types: "traction" (elastohydrodynamic) and hydromechanical. Note the major improvement in fuel economy (~ 25%) with the IVT over most of the speed range. Another factor to be considered on a steady state basis is the accessories. In general, these have been designed as add-ons and therefore, have not been well-integrated with the engine/transmission system (ref. 11) They operate at variable speed most of the time, appreciably off optimum design point, and consume a large percentage of the required road load. The air conditioning and alternator are the other large parasites that impact on fuel economy. The first of these is required only for passenger comfort. Figure 11 illustrates some of the accessory power demand versus engine speed. Constant speed accessories have the potential of improving fuel economy by about 10% and should, of course, be considered.

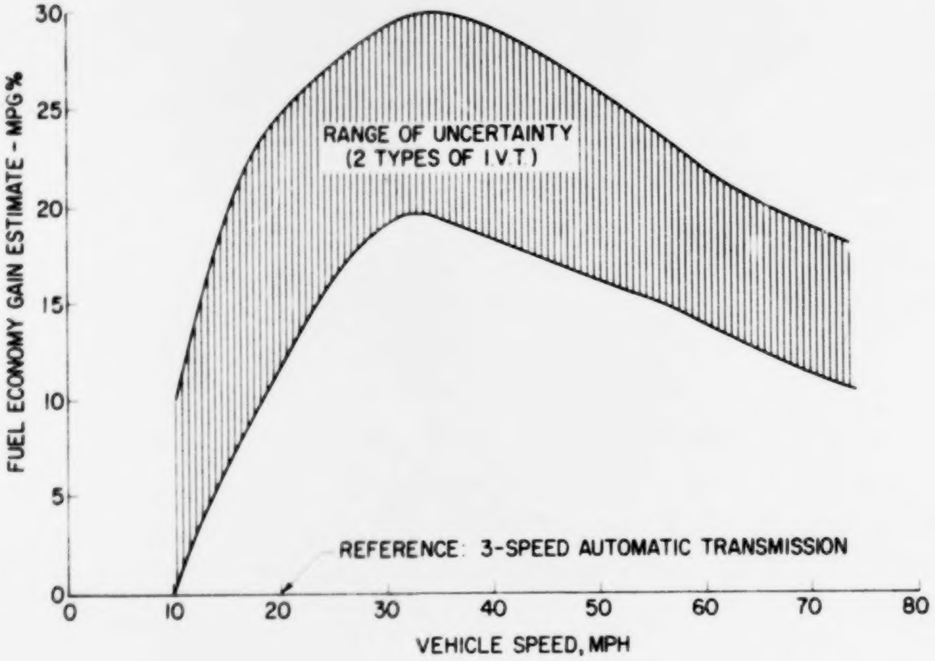


Fig. 10 The Potential Fuel Saving with Infinitely Variable Transmission

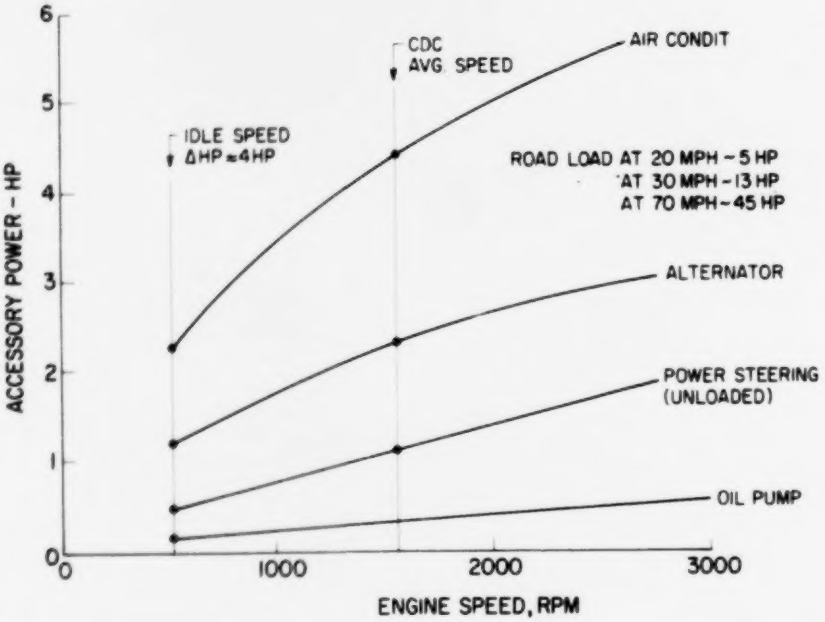


Fig. 11 The Potential Fuel Saving with Constant-Speed Accessories

FUTURE PROSPECTS - Fuel and Energy Storage

Figure 12 presents four different scenarios. The following assumptions are made with regard to domestic reserves: domestic petroleum reserves are increased by a factor of 5, and the automobile's share of these total resources remains fixed. Curve 1 represents the 13.6 mpg fleet. Curve 2 represents the phase-out of the 13.6 mpg fleet and replacement with an 18 mpg fleet in 100% production from 1973 on. Curve 3 is the same as Curve 2 until 1990, when production of a 28 mpg car fleet is gradually introduced so that by 1996, it is in 100% production. Curve 4 is the same as Curve 2 until 1985, when production of a 40 mpg car fleet is gradually introduced into full production by 1991, and represents 100% of the automobile fleet in the year 2000.

From 1973 to 2000, DOT-2 automobile population growth is assumed (1973 - 100 million vehicles; year 2000 - 160 million vehicles). This growth is approximately 20 million vehicles lower than extrapolated average historic growth.

To achieve scenario #4 will require a major industry/government R&D effort. Such an accomplishment would be comparable to our Apollo Program. If successful, such an approach can give us an additional 20 years over the baseline, Curve 1.

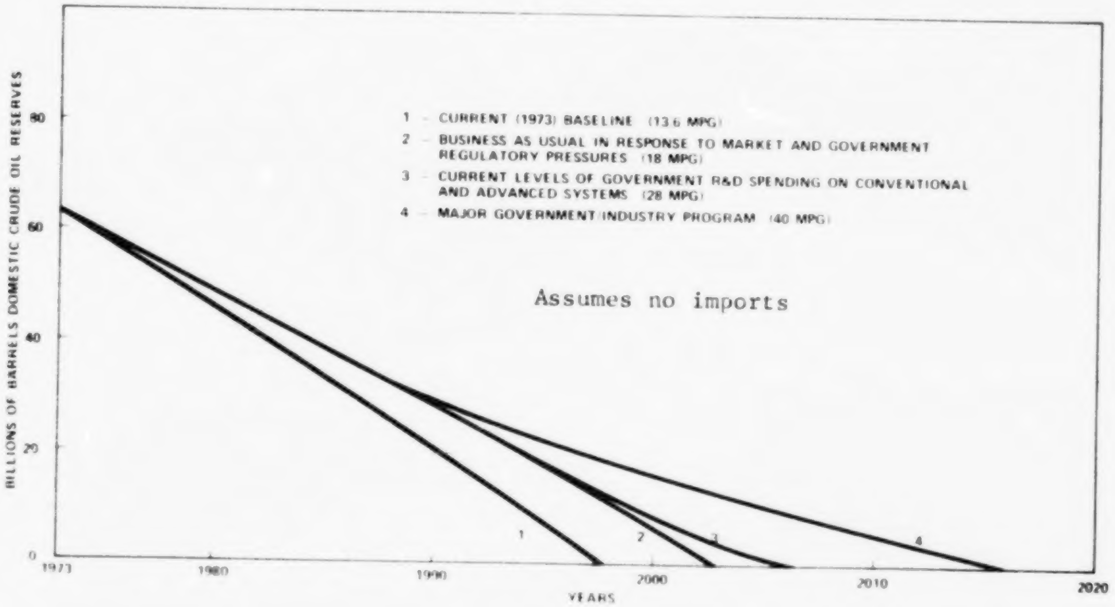


Fig. 12 Depletion of "Auto Share" of Domestic Oil Reserves

It is clear that CONSERVATION OF ENERGY must be our prime developmental goal, and, in particular, REDUCTION OF PETROLEUM USAGE. In this regard, there are two important strategies to be followed: 1) initiate vigorous R&D effort and introduce incentives that are conducive to early introductions of even small fuel savings by the consumer, and, 2) to introduce as rapidly as possible propulsion systems having major improvements in fuel economy. The importance of early introduction of any fuel savings has a compounding effect and is illustrated in Figure 13 (ref. 2). Note that automobiles having a national average of 28 mpg in fuel consumption introduced in 1980 produce greater fuel savings by the year 2000 than do 40 mpg automobiles introduced in 1985 or 60 mpg automobiles in 1990. This data was calculated assuming only 1/2 historic incremental automobile growth (1.35×10^6 autos/year, whereas between 1945 and 1973 the incremental automobile growth was actually 2.7×10^6 autos/year, ref. 12). While these fuel savings are very large and greatly affect our balance of trade, they are still not adequate to cope with our fuel needs.

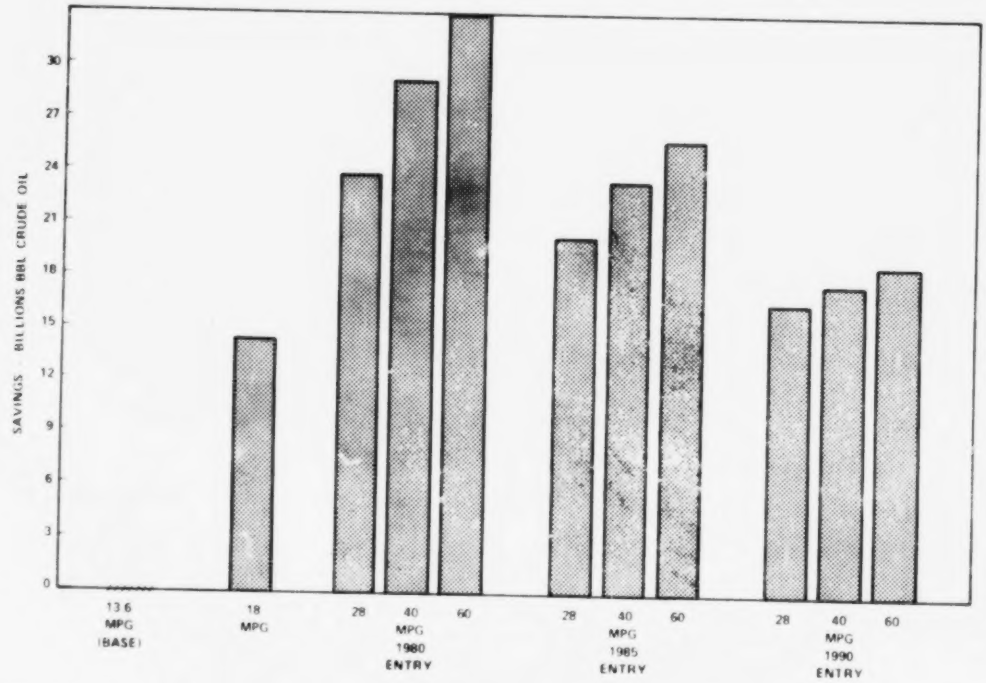


Fig. 13 Cumulative Fuel Savings (Auto Population Growth at 1/2 History)

Thus, assuming that the petroleum-based fuel reserves are very finite, one can then postulate that the economies of the system will change and allow the introduction of alternative sources of fuel and energy. During the 80's, one can expect alternative fuels derived from shale and/or coal to become available and begin to offset the rate of imports of crude oil (these can supply our energy demands for 300 years or more). Some of the properties of alternative fuels that are currently under investigation are given in Table V, which was generated by the authors from the data presented in refs. 15 and 16.

TABLE V PROPERTIES OF ALTERNATIVE FUELS

Fuel	Density lb/ft^3	Heat Value		**1982		M.Pt. °C	B.Pt. °C	Relative ease of storage	Relative Toxicity
		Btu/lb	Btu/ft^3	\$/MMBTU	¢/Gal.				
Hydrogen (coal)	4.4	51,700	0.23×10^6	9.90	30	-259	-253	6 (liq)	1
Hydrogen (water)				10.20	31				
Ammonia	42	8,586	0.36×10^6	7.65	37	-78	-33	4	5
Hydrazine	63	7,200	0.45×10^6	20.00	120	1.4	113	3	6
Methanol (coal)	49.4	8,572	0.42×10^6	3.85	22	-98	65	2	4
Methane (coal)	25.9	21,500	0.56×10^6	5.65	42	-186	-162	5 (liq)	2
Ethanol (by fermentation)	49.2	11,525	0.57×10^6	7.10	54	-112	78	1	3
Gasoline*	46	19,300	0.89×10^6	2.11	25.2		125	1	(4)
Shale: gasoline				2.65	31.5				
distillate				2.05	26.5				
Coal: gasoline				3.35	34.5				
distillate				2.75	36.5				

*Reference Fuel, Regular gasoline

**Based on 1973 constant dollar (10% discounted cash flow return on investment), ex tax at pump. 1973 tax on gasoline in large metropolitan areas was:

Nation	Tax ¢/gal.
USA	11.2
Japan	35.3
W. Germany	43.7
Gt. Britain	48.0
France	59.5

While these new fuels can be developed, the time and investment cost are very large. Developments are also required in fuel storage, handling, and transfer, since many of these fluids are best stored at cryogenic temperatures. The best of these fuels seems to be methanol extracted out of coal. Hydrogen seems to have better yearly applicability in aircraft than in automobiles.

The lead time required to generate an industry to provide these alternative fuels is such that its impact will not be felt until the year 2000. Figure 14 shows the results of a number of detail studies and approximately how alternative fuel sources may begin to alleviate the import problem.

Another approach is to consider electric vehicles which, of course, would not require petroleum fuel and are inherently low in emissions and noise. The problem here is primarily technological. We do not yet have high energy and power density batteries (ref. 17) or fuel cells that have a long life and are low in cost. Nor do we have high efficiency, low cost electrical motors and controls. There are a number of relatively small battery developments underway, supported by NASA, AEC, and NSF. These efforts are very low in funding, and the progress is very slow. In fact, the R&D effort in Japan on electric vehicles is considerably larger and much better integrated. Unless we do something in in this field, we should not be surprised if, at the turn of this century, the Japanese electric vehicles become a significant percentage of the propulsion system on our roads. Figure 15 compares energy and power density for several types of batteries and also several heat engines.

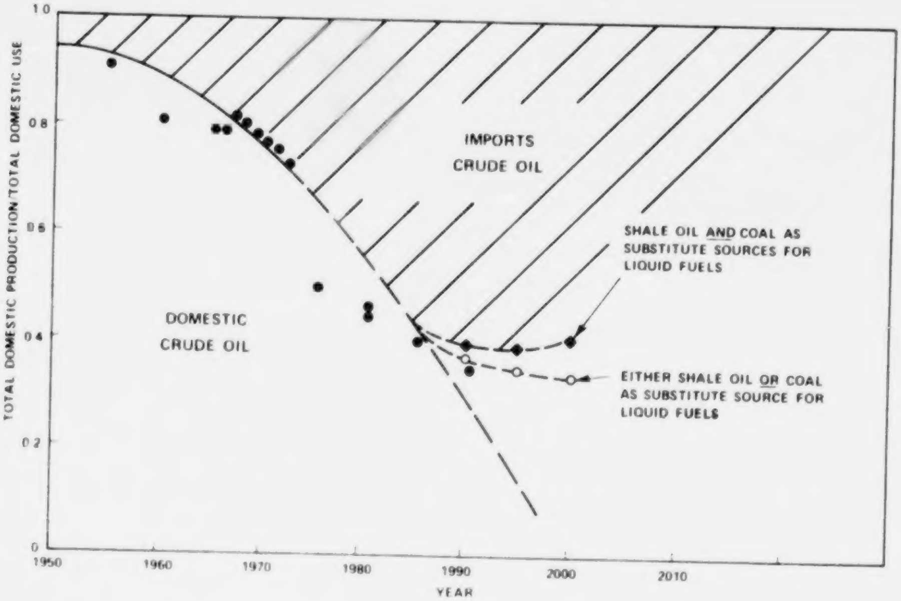


Fig. 14 Alternate Fuel Sources

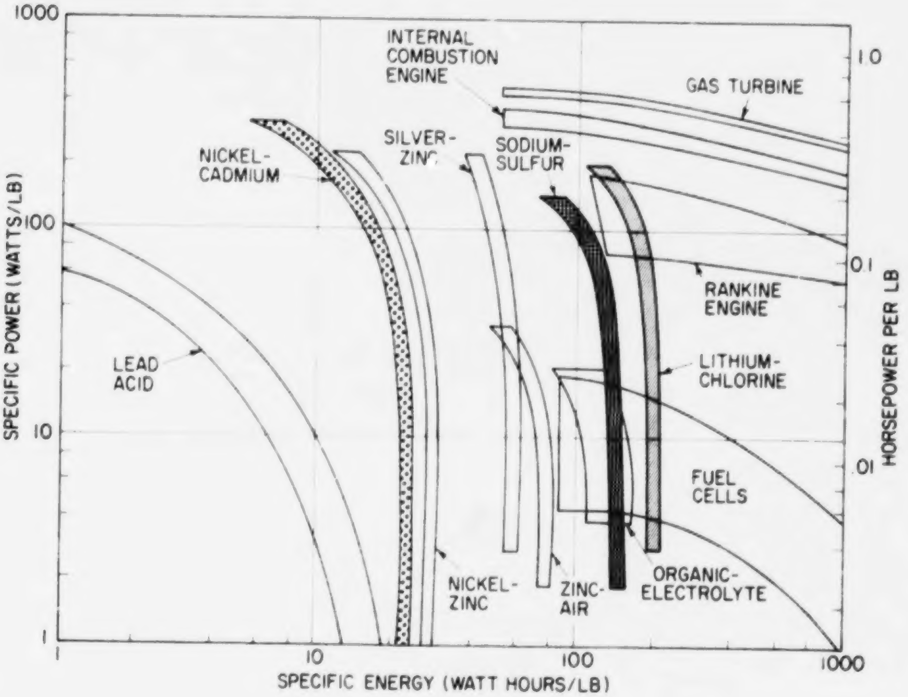


Fig. 15 Specific Power versus Specific Energy

In a recent EPA program to determine the impact of electric car use in Los Angeles, it was concluded that advanced battery systems would be required if one were to replace the first car in the family. The major improvement that is required for the electric vehicle is increased range. Figure 16 shows the range comparison among the various advanced batteries under investigation.

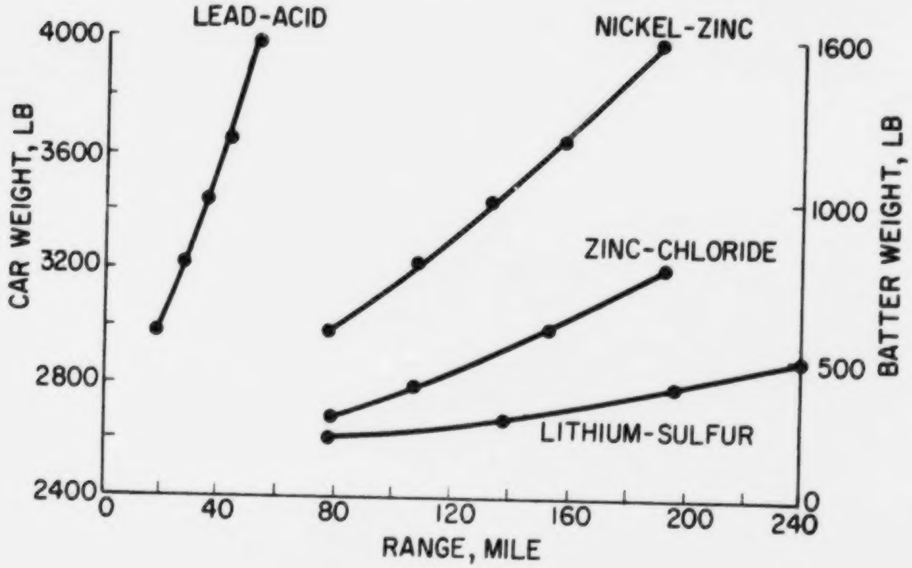


Fig. 16 Urban Driving Range of Future Electric Cars (SAE Metropolitan Cycle)

In the meantime, until high energy density batteries are developed, the hybrid systems are likely candidates. These could be heat-engine-electric, or heat-engine-mechanical (flywheel, ref. 18, or hydraulic). A few very modestly funded studies and developments on this subject are underway. These systems could improve fuel economy and represent a logical transition between today's heat engines, and future electric vehicles. They are readily adaptable to regenerative braking, which has a 5% fuel economy improvement potential. In addition, they can use lower horsepower engines and operate them more efficiently, thus producing additional fuel savings. The energy storage devices could be considered as another form of transmission with energy regeneration potential. Table VI compares several energy storage devices. The authors compiled this table from several sources, including ref. 18.

Another method for storing energy is in the form of heat. It has been shown that pure fluorides of Lithium, Aluminum, Sodium, or Magnesium or eutectic mixtures of these fluorides have extremely high heat storage capacity. Use of stored heat simplifies the engine and its controls. The heat stored takes the place of fuel and tank and eliminates the combustion process. It becomes the heater through which passes the engine's gaseous working fluid. Each of the energy-stored concepts have fundamental problems that seriously limits their application in today's market place. However, with the proper investment in research and development, these problems can be solved.

TABLE VI ENERGY STORAGE COMPARISON

STORAGE DEVICE		(ENERGY DENSITY) Watt Hours/lb	POWER DENSITY Watts/lb	Deep (75%) Discharge cycle Life, cycles
COMPRESSION OF GASES		4	> 4500	> 10^7
HYDRAULIC ACCUMULATOR		4	> 4500	> 10^7
ELASTIC DEFORMATION				
Steel spring		0.05	> 4500	> 10^7
Natural rubber band		4	36*	1000-5000
ELECTROCHEMICAL REACTION				
Lead acid battery	Presently	10	60	> 1000
Nickel cadmium battery	Available	12	300	1500-3000
Nickel-zinc battery		30	100	400
Zinc-air battery	Past 1980	30	30	400
Sodium-sulfur battery	Past 1990	100	120	1000
Lithium sulfur battery		110	120	1000
KINETIC ENERGY				
Cast Iron (Oerlikon Bus.)		4	> 1000	> 10^5
4340 Steel flywheel		15	> 4500	> 10^5
Maraging Steel flywheel		30	> 4500	> 10^5
Filament Composite		40	<10000	> 10^5

*Set to this value to facilitate cycle life and energy density comparison.

R&D PROGRAM

Table II identified the factors that comprise an automobile system. It was also pointed out that the system is highly complex with many interactive and conflicting parameters. In the early 1900's, there were several systems being developed; today, there are many more, and the financial risks are much higher. We cannot afford to make serious mistakes. The various propulsion systems discussed in open literature are in different stages of development. Some are in mass production, and others are only "paper" engines (Figure 17, refs. 3, 7, and 19). The issues of importance are also many, considerably more than there were in the early 1900's (Figure 1).

High risk, high payoff systems must be encouraged if we are to make the required impact. Today, practically all of these are only in the conceptual stage. The AAPS program of EPA is developing a computer program with a number of subroutines that will be able to quickly assess an engine/transmission/accessory system that is in any stage of development, including even one that is only a paper design.

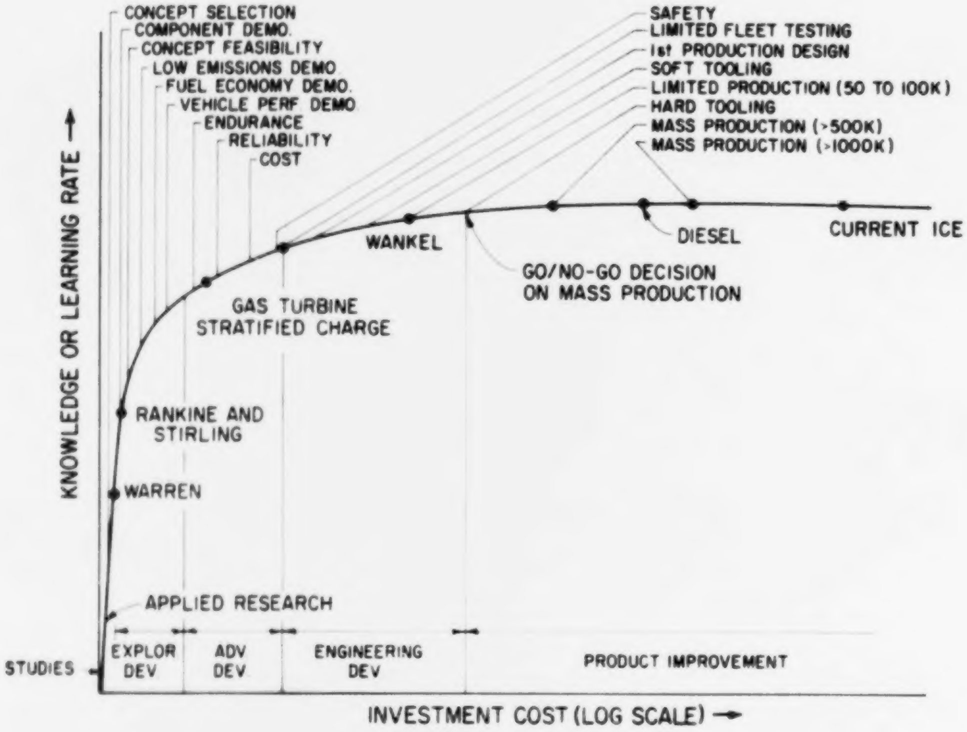


Fig. 17 Selection and Production Requirements

As pointed out throughout the paper, the main objective of the future R&D effort is fuel economy improvement, with several other secondary goals. Figure 18 illustrates the various areas that will have to be investigated in order to meet this objective. Some of these are short, others intermediate, and yet others are long-term developmental efforts. On short and intermediate bases, the minimum program goal should be doubling (20 mpg) present day fuel economy. The benefit of this accomplishment is portrayed in Figures 12 and 13. This improvement in fuel economy should be possible if we address ourselves to three main areas (Figure 19):

- Mission Cycle
- Power Train, Accessories, and Vehicle Design
- SFC Improvements.

It should be pointed out that the average overall efficiency of current internal combustion engines is only around 10%. On the other hand, stationary power plants have an overall efficiency of 40%, and stag cycles (Gas turbine-Steam Turbine binary cycle) have overall efficiency in excess of 50%. Thus, we have considerable room for improvement, and the 40 mpg longer-term objective is attainable, but will undoubtedly require new energy conversion systems.

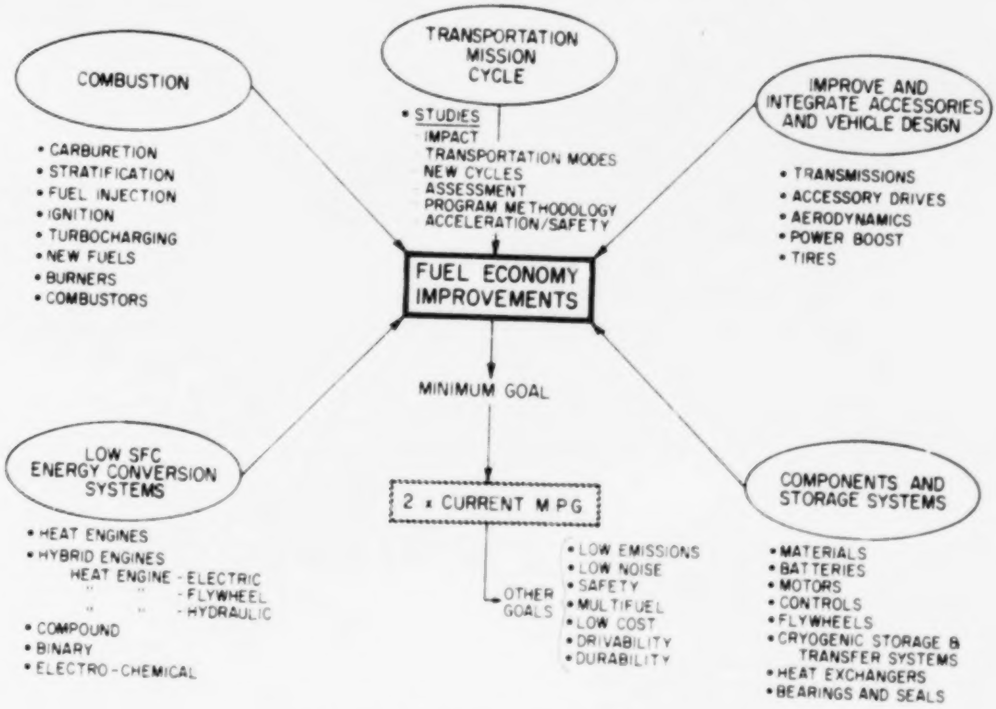


Fig. 18 Program Elements

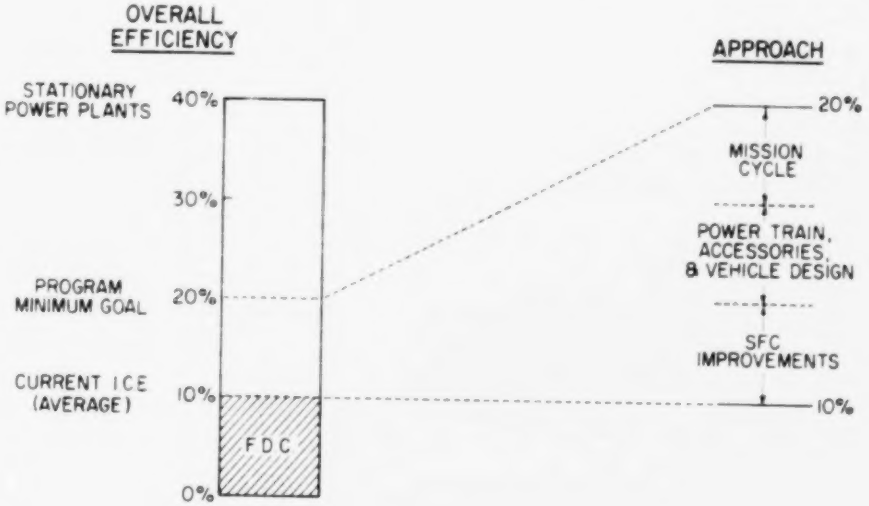


Fig. 19 Short and Intermediate Approaches to Fuel Economy Improvements

LONG-RANGE PERSPECTIVE (Crystal Ball Gazing)

The paper would be incomplete without presenting some long-range perspective. This, of course, requires a certain amount of guessing and crystal ball gazing. One of the authors has recently made his educated guesses (ref. 3).

In this paper, we would like to present only a general perspective. The various prime movers presently being discussed in open literature have been classified in Table VII. They are divided into three broad categories:

- Internal Combustion
- External Combustion
- Other (or combinations).

TABLE VII PRIME MOVER CLASSIFICATION

PRIME MOVER	HEAT ENGINES		OTHER
	Internal Heat Addition (Internal Combustion)	External Heat Addition (External Combustion)	
POSITIVE DISPLACEMENT			
Recip.	Otto-Spark Ignition Diesel Stratified Charge	Rankine Stirling Warren	
Rotary	Wankel	Warren	
TURBO		Brayton (Gas Turbine) Rankine	
COMPOUND	← Combination	→	
BINARY	← Combination	→	
HYBRID			Heat Eng. - Electric " " - Mechanical • Flywheel • Hydraulic
ELECTRO-CHEMICAL			Battery Fuel Cell
KEY FEATURES	• LOW COST • SAFE • GOOD DRIVEABILITY • MASS PRODUCED OR READILY CAPABLE OF MASS PRODUCTION • USES CONVENTIONAL MATERIALS • HIGH DURABILITY	• GOOD FUEL ECONOMY • MULTIFUEL CAPABILITY • ADAPTABLE WITH NEW ENERGY SOURCES • LOW EMISSIONS	

Some key features for these categories are identified. Most of the ICE are already being mass produced. Thus, it will be very difficult to displace them. There are major capital investments, experience and vested interests. Yet, they are being challenged today, and there are good reasons for this. It is questionable whether they will survive as leading prime movers past this century. Inherently, they have several disadvantages, the prime one probably being the internal heat addition feature, which makes multifuel capability, good fuel economy and low emissions more difficult to achieve.

As we crystal ball gaze, we see the utilization of new energy sources by the automobile (Figure 20 (ref. 2)). It is expected that first, the impact will be with alternative fuels (Figure 14), and then with nuclear and solar energy (Figure 21). The alternative fuels could be gasoline or distillate extracted from coal and/or shale (Table V). Their prices should be comparable to crude oil extracted from the ground (ref. 16). In fact, one way for us to control the prices of foreign oil and become independent or self-sufficient is to develop our capability to extract gasoline and distillate from coal and shale at economic prices.

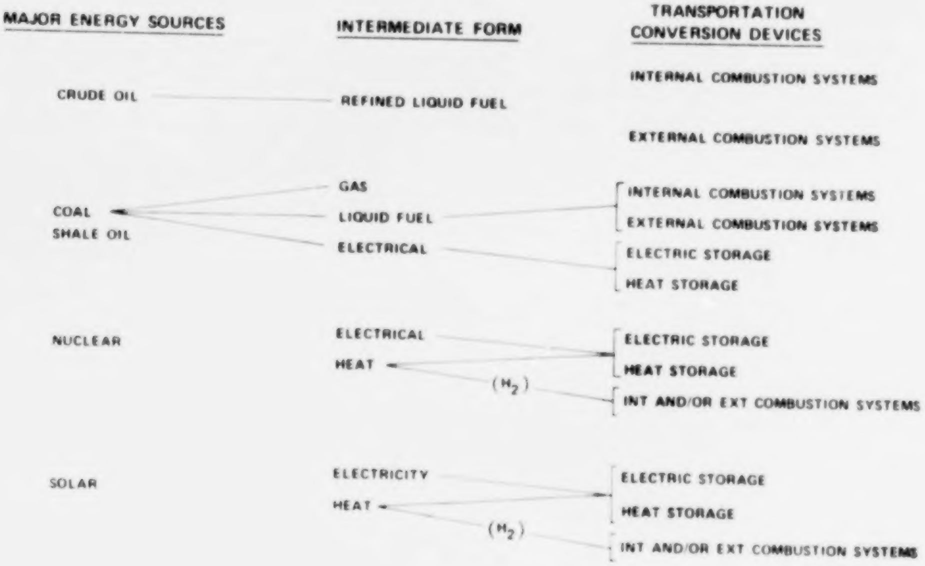


Fig. 20 Energy Sources for Transportation

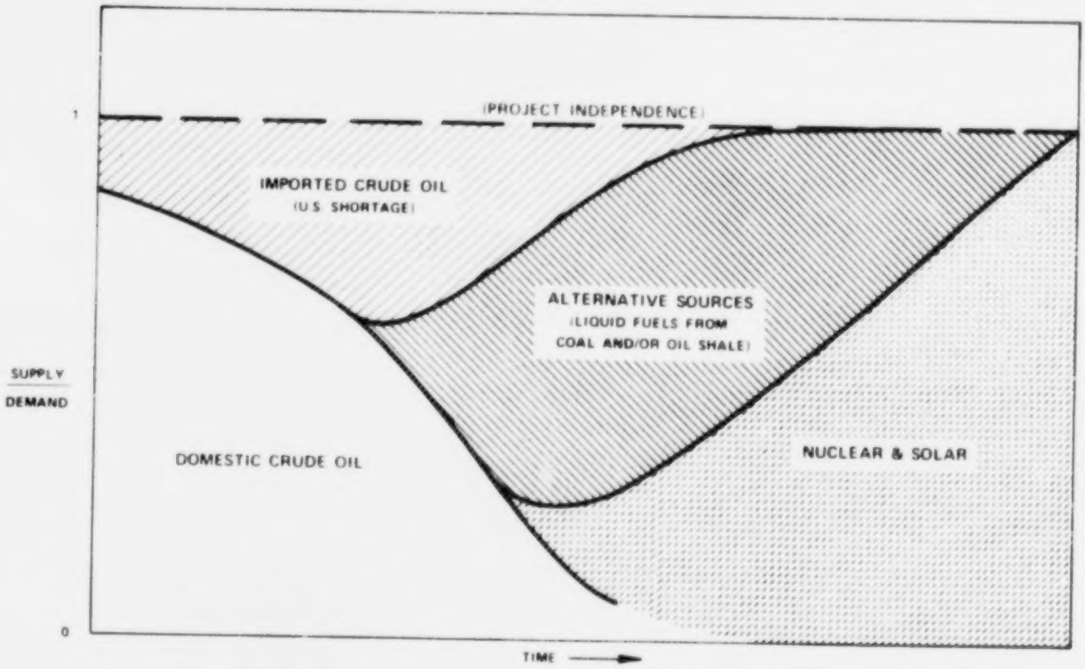


Fig. 21 Future Projection of Energy Sources for Transportation Fuels

At a later date, electric vehicles may come into being; these will depend on the technological advances in batteries, motors, and controls. These systems could use nuclear or solar energy for making the electrochemical batteries and also for charging them. One can readily envision parking meters coupled to solar collectors that are used for recharging of batteries. One could go a step further and envision the vehicle body being made up of solar cells that are used for continuous battery charging.

Of course, nuclear and solar energy can also be used for making other fuels, e.g., hydrogen from water. One could also envision cryogenic distribution systems that will not only greatly improve electrical power transmission, but will also provide fuel for transportation. There are many possibilities, and they are only limited by our imagination and economic considerations.

The challenges are many. The accumulated payoff by the year 2000 is in the hundreds of billions of dollars. It is only necessary to provide the proper motivation and resources to get the goals accomplished on a timely basis. Very seldom can we point to a program that has such a major cost benefit to our nation and the welfare of our economy. It is important, therefore, that government, industry, universities, and the public work together in harmony to meet this challenge.

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System Analysis of Drive Units

P. Hofbauer, B. Wiedemann
Volkswagenwerk AG Wolfsburg
L. Siencnik, W. Fausten, Dr. U. Schmidt
Klöckner-Humboldt - Deutz AG, Köln

The objective of the system analysis is to facilitate a decision of competitive alternative power plants. The model logic on which the analysis is based is also valid in general for other technical problems.
The decision basis is formed by time dependent functions which change according to new requirements for power plants (e.g. fuel economy, low pollution) and to the advances in technics.

La mission de l'analyse systématique est de fournir une aide décisive lors du choix des solutions concurrentielles pour les mécanismes de propulsion.

La logique des modèles de l'analyse est en général valable également pour les autres problèmes techniques.

La base de la décision est formée de fonctions dépendant du temps qui se modifient suivant les exigences pour les nouveaux mécanismes de propulsion (par exemple, la consommation d'essence, les émissions plus faibles des gaz d'échappement et en fonction des progès de la technique).

Zielsetzung dieser Systemanalyse ist es, eine Entscheidungshilfe bei der Auswahl miteinander konkurrierender Alternativen von Antriebsaggregaten zu geben. Die Modellogik ist allgemein für technische Problemstellungen gültig. Die Entscheidungsbasis bilden Größen, die aufgrund der sich mit der Zeit ändernden Anforderungen an die Antriebsaggregate und bedingt durch den technischen Fortschritt als zeitabhängige Funktionen darstellbar sind.

4 3

System Analysis of Drive Units

This analysis has been prepared as a decision-making aid for the selection of competing alternatives of automobile power plants. Although the model logic in general applies to the formulation of technical problems, it has been concentrated on the area of automobile power plants in line with the objectives of this paper.

The decisions are based on the concepts shown in the block diagram below. These concepts can be rendered as time-dependent functions because of the time-dependent changes in requirements on automobile power plants, and because of the progressing state of the art.

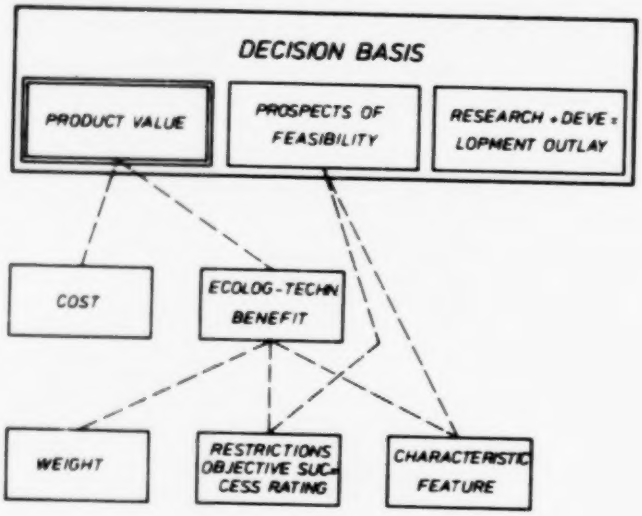

Fig. 1 DECISION BASIS

The Product Value is the decisive quantity. It is the quotient of benefit and cost.

Benefit is the objective success rating reached by the alternative in regard to the objective established by the scope of product application. This paper analyses the ecological/technical benefits only. It does not include additional benefit areas, e.g. scientific, political, military, societal and other benefits.

A system of objectives has been set up with three hierarchical levels of decreasing complexity, based on the component objectives relevant to automotive power plants (Tables I and II).

This system should permit as full as possible a complete supplementation, including future component objectives. It intends to provide a quantified description of future scenarios for the ranges of application.

Table I OBJECTIVE SYSTEM (TECHNICAL CONSIDERATIONS)

1000 Functional quality	1100 Control requirements (Operating comfort)	1101 Elasticity (Number of gears)
		1102 Time behavior
		1103 Engine braking effect
	1200 Availability (Breakdown susceptibility)	1201 Reliability
		1202 Maintenance requirement
		1203 Life
	1300 Performance under special conditions	1301 Start - up behavior
		1302 Performance loss at high altitude
		1303 Energy available for heating
	1400 Vibration level (Oscillation behaviour)	1401 Degree of Uniformity
		1402 Balance of masses
	1500 Fuel requirements	1501 Multi-fuel capability
		1502 Operating Range(Heat Value)
		1503 Operating danger
2000 Installation suitability	2100	Power to Weight Ratio
	2200	Power to Volume Ratio
	2300 Engine Configuration (Shape)	2301 Length
		2302 Height
		2303 Width
	2400 Suitability for mass production	

Table II OBJECTIVE SYSTEM (ECOLOGICAL CONSIDERATIONS)

3000 Preservation of raw materials	3100 Energy	3101 Oil
		3102 Natural gas
		3103 Coal
		3104 Nuclear energy
	3200 Material	3201 Aluminium 3202 Chromium
		3203 Cobalt 3204 Copper
		3205 Iron 3206 Lead
		3207 Manganese 3208 Molybdenum
		3209 Nickel 3210 Platinum group
		3211 Magnesium 3212 Tungsten
		3213 Titan 3214 Vanadium
		3215 Zinc 3216 Tin
4000 Environmental protection	4100 Pollutants	4101 CO
		4102 NO_x
		4103 $C_n H_m$
		4104 Particulates
	4200 Noise	
	4300 Waste	

The system of objectives includes the

technical areas	qualitative rating of operability
	feasibility of incorporation into vehicle unit
ecological areas	conservation of resources
	environmental protection

The objective system was prepared with a general view to the power units (black box). Emphasis was not placed on the kind of power plant but on the result of energy conversion. This means that this systems analysis does not directly review any specific engine data, such as compression ratio etc.

The individual component objectives have different significance. Consequently, it becomes necessary to weight these component objectives one against the other. The time-dependent weighting functions should be prepared by qualified personnel. The range of scatter of the established functions may be narrowed down by application of a method used in prognosis making a statement more precise, i.e. the DELPHI method.

The percentile approximation is provided by the objective success rating of a component objective for the percentage approximation of the alternatives to an imagined engine that would meet 100% of the relevant component objective. The objective success ratings are monotonic functions of the characteristics between the standards and the limits of feasibility. The limits of feasibility must be taken into consideration when a selection is made of the restrictive system. A group of competent personnel, too, should prepare the functions of the objective success rating, and the results should be condensed by way of the DELPHI method.

The characteristics describe the alternatives and can only be given, for future developments, in the form of scatterbands.

The ecological technical benefit results from the characteristics functions $M_i(t)$, the functions of the objective success rating $ZG_i(M_i)$, and the weighting functions W_i (t).

$$\text{ÖTN}(t) = \sum_i ZG_i \left(M_i(t)\right) W_i(t) \frac{1}{100} \qquad (1)$$

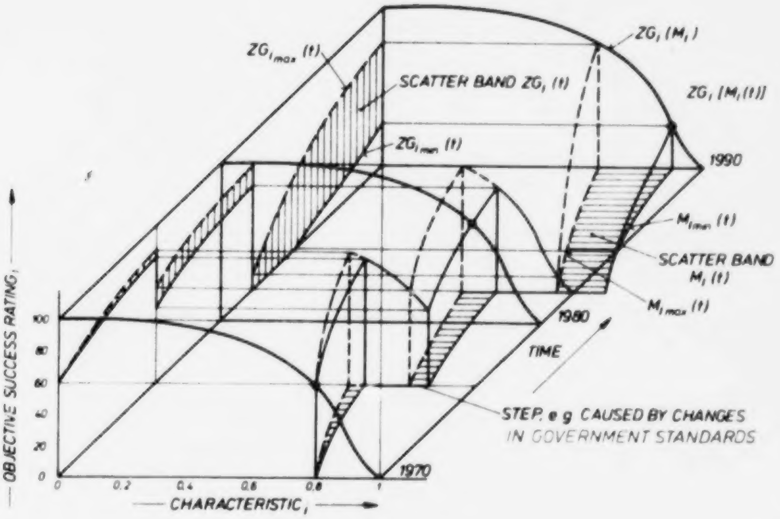

Fig. 2 OBJECTIVE SUCCESS RATING

The cost breaks down into
cost of production
consequential cost
operating cost

These may be discounted on the time unit.

The anticipated degree of realization (RA) indicates the probability that the alternatives will reach the demands set by the range of applications. The anticipated degree of realization follows from restrictions and from the characteristics.

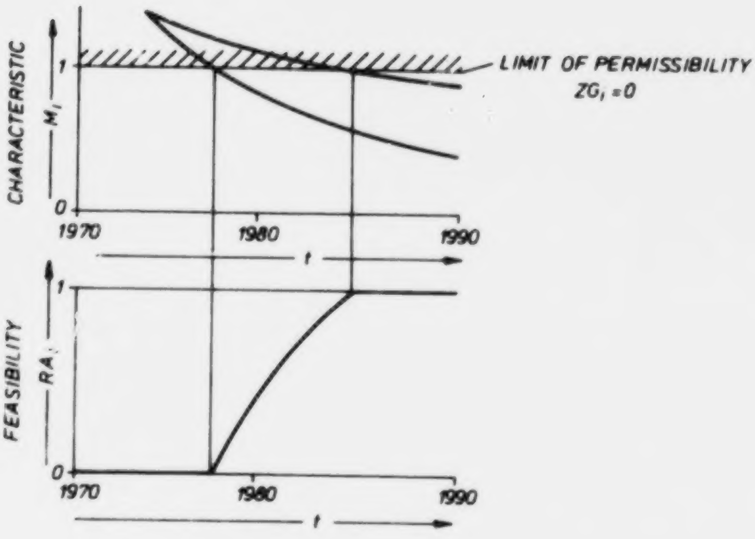

Fig. 3 COMPONENT OBJECTIVE FEASIBILITY

Examples for demonstration were computed in two different ranges of application:

I. For the passenger - car segment, we studied a compact car for city and piggy - back traffic (e.g. on railroad), with a gasoline engine as alternative

II. As for the truck segment, we studied a transporter vehicle in INTER-CITY traffic with a diesel engine as alternative.

To test the system analysis several alternatives from the morphological system of power plants were run through by VW. A group of people from VW Research Department acted as judges but they cannot be considered to represent the opinion of the VW factory. Considered statements are exspected from a group of experts who will be approached by the BMFT. As the existing results are, on the one hand not adequately substantiated and on the other hand uncorrect assessment can lead to serious prejudices, the results will not be published as a paper but brought up for discussion at the Nato Symposium.

The presented methodology is to be further refined with the aid of experts in empirical testing. The particular objective is to set up a data bank that would permit continuous expansion of the data available.

SESSION 7

LPPSD-Programs
of the Signatory States of the Memorandum

7ème SESSION

Programme LPPSD
des Etats signataires du memorandum

THEMENGRUPPE 7

LPPSD-Programme
der Signatarstaaten des Memorandums

MINUTES

Conference of Government Representatives on the
Committee on the Challenges to Modern Society
Low Pollution Power Systems Development Project
Düsseldorf, Federal Republic of Germany, November 8, 1974

1. Delegations. The Head of each Delegation, or his representative, and additional delegates present were as follows:

   a. United States of America (Pilot Country): Fitzhugh Green (representing Head of Delegation and Chairman of the meeting); John J. Brogan; George M. Thur; Cameron Sanders; and John H. Ludwig (Secretary)

   b. Canada: A. C. Gullon (Head of Delegation)

   c. Federal Republic of Germany: Dietmar Frenzel and Hans-Ludwig Dreissigacker (Co-Heads of Delegation); Dietrich Hartmann; and Jürgen Bandel

   d. France: P. Dreyer (representing Head of Delegation)

   e. Italy: G. F. Savonuzzi (representing Head of Delegation)

   f. The Netherlands: L. C. van Beckhoven (representing Head of Delegation)

   g. Sweden: Olle Ljungström (Head of Delegation)

   h. United Kingdom: George Donald (Head of Delegation); R. J. Palmer; and E. Tirrell

2. Mr. Fitzhugh Green, Associate Administrator for International Activities, U.S. Environmental Protection Agency, representing the Head of the Delegation for the United States (the Pilot Country for the CCMS/LPPSD project) chaired the meeting of delegates that convened at 12:00. Discussions at the meeting were informal, and concerned for the most part the items listed on an agenda prepared by the German delegation as the result of informal discussions at a meeting of the delegates on November 7, 1974. The meeting began with general statements by the Heads of Delegations concerning the CCMS/LPPSD project, followed by specific discussions for each of the items on the agenda, listed herein in the order considered at the meeting following the opening general discussion.

3. General Discussion. During the opening general discussion, comments were made concerning various features of CCMS cooperation in addition to the LPPSD project. In general, satisfaction was expressed concerning the operation of the project to date and the prospects for future cooperation with an enlarged scope of activities, although there were differences in the items to be included and the time frames selected for such various activities. (These views are discussed specifically under the topics included in the agenda.)

It was noted that future participation for the United States would be split between the Environmental Protection Agency (EPA) and the Energy Research and Development Administration (ERDA) as the result of recent Federal legislation in the United States. A future change of the name of the project was suggested to reflect the enlarged scope of activities to be carried on under the project, if indeed mutual agreement could be reached during the coming year to expand the present scope of activities. Some delegates stressed the need to expand the scope of the project beyond the present reporting of activities and project findings to include significant coordination and cooperation on a bilateral or multilateral basis, such coordination/cooperation to be of direct assistance in meeting program goals established in various countries. It was suggested that every effort should be made to initiate such cooperation as soon as possible, and that this subject should be an area for major discussion at the next CCMS/LPPSD project meeting.

It was pointed out, however, that activities under the program should be kept in consonance with the established need to control air pollutants based on scientific evidence as well as political consideration. It was expressed that the factor of time periods selected to control pollutants was probably the major significant differences in the objectives of various countries for control of pollution, as well as the degree of control needed for sources to effect the quality of ambient air desired.

The delegates were cautioned, with regard to expansion of the project into additional areas, to assure that conflict did not occur with other NATO/CCMS projects.

4. Noise Abatement. In general, the subject of noise abatement was generally agreed to be a high priority area for increased emphasis and cooperation. Various facets of the noise problem concerning road transportation were pointed out: measurement, technology of control, and

interaction and trade-offs with other factors involved in vehicle development (e.g., pollution control, fuel consumption, economic considerations).

Agreement. It was agreed to develop a specific project for cooperation in this area and, as a result, Sweden, with assistance from the United States, will study the formulation of and the possibility of taking on a project for presentation and review at the next meeting of the CCMS/LPPSD project. The need for a meeting of a small group of experts to further assist in this endeavor was proposed and will be organized, if required, as the definition of the project develops.

5. Combining the LPPSD and RSV Projects. There was considerable discussion on combining the NATO/CCMS projects on development of low pollution power systems for vehicles and vehicle safety. It was agreed that, although there were many interactions and conflicting demands between the two programs (e.g., the effect of weight on fuel economy, conservation, and to some degree, emissions), the major objectives of the two programs did not lend themselves well to combining, at least in the present stages of development of both programs. Generally it was expressed that very close and timely exchange of activities and developments between the two projects might suffice. However, due to the interaction of the programs in the light of changing goals, it was suggested that something more than mere exchange of information during respective meetings of the LPPSD and RSV projects might be needed. Additionally, it was expressed that, in a sense, coordination of the two programs would be brought together ultimately by industry during

manufacture. Further comment suggested that direct coordination would be more appropriate during the prototype stage than in the present developmental stage. Because of these divergent views, the chairman suggested that the decision to combine or not to combine the two projects be deferred until the next meeting.

Agreement. During the coming year, Italy will prepare a paper outlining the interactions of the two projects and the need for coordination during various stages of development, and suggest various alternatives available to effect the required coordination; such paper to be reviewed at the next LPPSD project meeting as the basis for determining whether a program for coordinating activities is needed and, if so, the program to be proposed to the RSV project.

6. Bilateral/Multilateral Projects. As reported previously herein (Item 2/General Discussion), many delegates expressed interest in initiating bilateral or multilateral cooperative projects. Specifically, several areas had been mentioned during the symposium or in previous discussions at this meeting: ceramics, Stirling engine, and noise. However, to facilitate the choice of areas where cooperation would be desirable, the United States suggested the preparation of an "overlay" which would compare areas of activity in all countries (including objectives and funding) with a listing of needed research and development, and agreed to undertake the preparation of such an analysis.

Agreement. Consequently, it was agreed that each country would furnish to the United States and other countries as well (in accordance with a brief format to be developed by the United States) a listing of projects outlining briefly the scope of the project, funding, and time periods involved. The United States will then prepare the "overlay" and make it available to all countries as background information for considering the desirability of bilateral or multilateral cooperative projects. Countries can then propose, based on this and other information as appropriate, suggested areas for cooperation and the specifics of cooperation at the next meeting of the CCMS/LPPSD project.

Further, with regard to the overall program development in the various countries in the LPPSD area, it was suggested that all countries undertake an active program to stimulate research and development in the private sector. The reporting of the "overlay" comparison as a part of future symposia would be helpful in this regard in that it would more specifically pinpoint the awareness of need--the first step in initiation of additional projects.

7 Standardization. Views on the practicability of cooperative projects on standardization (with regard to vehicle test cycles, emission measurements, and noise measurement) were quite divergent and ran the gamut of: (1) no practicability due to preemption by political decisions already made and differences posed by varying environmental conditions; (2) restriction of standardization to measurement methods only (although this was not universally accepted due to the need to relate measurement methods to the test cycle); to (3) an expression of the advantages, particularly to manufacturers, of having only one test cycle and measurement program. The question was not that this was an area of mutual interest, but how do you accomplish such a program so as to overcome

the multitude of difficulties envisioned (both political and environmental) to assure results commensurate with the effort to be expended.

Agreement. Since no clarification of the complexities involved could be resolved at this meeting, it was agreed that the Federal Republic of Germany will develop a paper on the practicability of cooperative activities on measurement methods for both vehicle emissions and noise. Such paper will be reviewed at the next meeting of the CCMS/LPPSD project as the basis for discussion and development of possible cooperative projects.

8. Fuel Consumption and Economic Considerations. No specific action was taken regarding separate projects on fuel consumption and economic considerations on the basis that these factors are not separable from and are already incorporated to a large degree into the LPPSD project, principally as the outcome of worldwide resource shortages, including energy. It was further suggested that the interaction of these factors with other demands made it difficult, if not impossible, to separate them in vehicle design and production and, thus, any attempt at such separation must be approached with caution.

9. Socio-Economic Effects. Interest in increasing the scope of the LPPSD project to include specific projects on socio-economic effects varied widely depending on the present interest and activities in this area in the various countries. Activities varied from a small to no effort in several countries to more extensive effort in others, e.g., the United States. Generally it was expressed that an exchange of

information on a timely basis, particularly by those who have a greater need for such studies to those with a lesser need, would be adequate to keep all countries aware of the methodologies involved, as well as the results. The complications involved in comparing the results of such studies, due to the differing socio-economic backgrounds of various countries, was pointed out. The German delegate indicated that an attempt would be made to incorporate socio-economic factors into their systems analysis for competitive alternative power plants and would report progress at the next LPPSD project meeting. The Swedish delegate pointed out that the National Swedish Board for Technical Development's Powerplant R & D group had taken on a subprogram on "Evaluation Criteria LPPSD" and was planning a later exchange of views with the EPA, USA.

Agreement. The United States agreed to make available to all countries reports of studies completed by the United States over the past several years and future reports as they become available.

10. Next Symposium. The Memorandum of Understanding (MOU) on the CCMS/LPPSD project specifies annual meetings between representatives of the signatory countries. The scope of the meetings, however, is the option of the LPPSD project delegates, depending on varying circumstances from year to year. For the first two years under the MOU, symposia have been held describing program needs and research and development results.

In considering the program to be adopted and the location for the next LPPSD project meeting, several views were expressed as follows: (1) yearly meetings as specified in the MOU are conducive to keeping the project moving to assure forward progress; (2) the program should be expanded (as already reported in discussions of specific items) to cooperative activities; (3) meetings yearly at a governmental level to exchange political and program views and a symposium every two or three years to report progress, in particular, technical results; and (4) meetings yearly to include both governmental level discussions plus a symposium, the latter to stimulate interest and activities outside the governmentally supported area and effect timely dissemination and exchange of technical progress. In this latter regard it was pointed out that most of the participants in the symposia have been industry representatives.

Following discussion of the suggestions offered, it was tentatively agreed that symposia similar to the two already held would be scheduled not more often than every second year, and that the principal focus of attention in alternate years would be on exchange of political and program views. The next meeting of the LPPSD project would, then, be scheduled for around November 1975 and, as already indicated herein by the various activities already agreed to, would include not only exchange of political and program views, but for the most part would focus on exploring the possibilities for, and, as appropriate, development of bilateral and multilateral cooperative projects. In this regard it was deemed pertinent for each delegation to include industry representatives as would be required to develop desired cooperative projects.

As to the location of the meeting, no commitments could be offered until the nature of the program and extent of activities to be undertaken at the meeting were specified in greater detail.

Agreement. Consequently, it was agreed that the United States would develop an agenda for the meeting to be held around November 1975, and, based on the proposed agenda, would: (1) determine whether a two-day or a three-day meeting would be appropriate, and (2) canvass the signatory countries to elicit their interest in hosting the third meeting of the CCMS/LPPSD project.

11. Adjournment. After unanimous expression of grateful thanks to the Federal Republic of Germany for the sponsorship of the Second Symposium, which all agreed was most excellently planned and carried out, the meeting adjourned at about 14:30.

Reports of the Delegations
on the National Sponsorship Program

United States of America	
J.J. Brogan	(BR)
V. Esposito	(ES)
France – P. Dreyer	(DR)
Netherlands – L.C. van Beckhoven	(BE)
Sweden – O. Ljungström	(LJ)
United Kingdom – G. Donald	(DO)
Federal Republic of Germany	
D. Frenzel	(FR)
H.L. Dreisigacker	(DR)
H.P. Neuhaar	(NE)

Report of the U.S. Delegation
by J.J. Brogan

In the United States over the past year there has been increased awareness and recognition of the role of the automobile in the total petroleum energy consumption, the relationship of auto safety and emissions on this petroleum energy consumption and in particular in the inefficient conversion of petroleum energy to provide propulsion as applied to automobiles. However, there are nearly 100 million vehicles on the road today in our country and power plants of considerably higher efficiencies are not near to production. This indicates the need for a strategy to reduce petroleum energy consumption for vehicles already in use, for new model vehicles with internal combustion engines to be produced over the next ten years, and for conducting agressive programs of research and development on alternative power plants and fuels.

As far as vehicles on the road are concerned, our government has reduced the maximum speed limit from 70 to 55 mph to effect a reduction in fuel consumption nationwide. At the same time the Department of Transportation is working on means to improve traffic flow, to better understand the price elasticity of gasoline, and to encourage better utilization of the automobile and to promote public mass transportation.

For new motor vehicles produced before 1980, our President is seeking cooperation with the auto industry to achieve a 40 percent improvement in fuel economy.

As far as research and development on alternative engines and finds the total Federal budget in the last fiscal year amounted to about $ 20 million for all agencies with $ 12 million specifically going to the Environmental Protection Agency for the kinds of work reported on this week at this symposium. Since the EPA program began in July 1970, total expenditures have been $ 35 million.

The ongoing EPA program is in the process of being transferred to a newly forming government agency which will be responsible for all energy related research and development. At the present time, this program can be divided into three major categories:

1. Evaluation of new power plants
2. Energy efficiency improvements applicable to international combustion engines
3. Alternative fuels research.

Under item 1: Our work on the Rankine and Brayton cycles has been reported on in this Symposium. Similar work is about to begin on the Stirling cycle engine with use of combustors and with heat storage techniques.

Projects underway to improve energy efficiency include the demonstration of a Rankine bottoming cycle to Diesel trucks, development of a continuously variable transmission, new methods for driving engine accessories and investigations into the feasibility of turbocompunding the conventional engine.

The alternative fuels of interest to us are not derived from petroleum and which are available in abundance in the United States, these include:

gasoline-like fuel from coal,
gasoline-like fuel from shale,
methanol from coal, and
hydrogen from electrolysis of water.

It is simply too early to tell whether this program wellexpanded in scope in the very near future. If it does, I would expect it to appear in such areas as development of lightweight lightduty Diesels, hybrid systems and battery powered electric systems. Also it is likely that the pace would be accelerated in ongoing ceramics process development.

Well, then that briefly sums up where we are today.

I would like to introduce Dr. Vincent Esposito, Director of Vehicle Safety Research in the U.S. Department of Transportation.

Report of the U.S. Delegation
by V. Esposito

Background

Ladies and Gentlemen, it is indeed a pleasure for me to be with you today representing the National Highway Traffic Safety Administration of the U.S. Department of Transportation. Our Administration has been working closely with the Environmental Protection Administration's Advanced Automotive Power Systems Program to ensure a coordinated approach to solving the interacting and often conflicting problems of auto safety, fuel economy, and exhaust emission control.

Certainly, today's energy and environmental crises demand that we search for fuel efficient, low-polluting motor vehicles. This Second Symposium on Low Pollution Power Systems Development underscores the fact that all major auto-producing nations are searching for and finding new solutions to the fuel economy and emissions problems.

Equal in importance to these two factors, however, is safety. Major steps have been taken, especially in this decade, to improve vehicle and highway safety for the motoring public. Even more important life-saving safety advances are on the horizon. In a companion program to this week's conference, the auto-producing nations of the world have been working together, especially since 1970, to improve the safety of tomorrow's vehicles. This cooperative effort, the International Experimental Safety Vehicle Program, has been carried on under the sponsorship of the NATO Committee on the Challenges of Modern Society and through individually negotiated bilateral agreements between the U.S. Department of Transportation and the Department or Ministries of Transport of the United Kingdom, Federal Republic of Germany, Japan, Italy, France, and Sweden. Of course, we all recognize that safety advances must be made in concert with economy and emission requirements. A "safety at any price" policy is not an acceptable solution. On the other hand, we cannot recklessly sacrifice thousands of lives in order to save barrels of oil.

Weight and Safety

The primary link between vehicle safety and vehicle performance (in terms of its economy and emissions) is weight. Other factors being equal and for a similar driving scenario, the heavier the vehicle, the more the demands in terms of engine performance and fuel consumption. Thus, one of the logical ways for manufacturers to strive for improved fuel economy, along with a better control of total vehicle emissions, is simply to emphasize smaller and lighter cars. Indeed, the dramatic upsurgence in the demand for compact and subcompact vehicles that occurred at the height of the energy crisis last year illustrates that this link between weight and fuel economy is one quickly grasped by the motoring public.

Not so easily grasped nor so immediately apparent to the public is the fact that this economy-motivated reduction in weight, if not properly engineered, may incur a serious safety penalty in terms of deaths and injuries from highway collisions. To illustrate this link between vehicle weight and safety, a brief review of some current accident research is appropriate here.

There have been a number of studies in the United States using accident data to investigate the relationship between car weight and safety. Unfortunately, each investigator established his own weight classes and assigned the makes and models to his classes by using some average weight, so results are not directly comparable. The effect is not too serious for generalized results, but absolute numbers cannot be obtained.

The question of involvement rate also clouds the weight and safety issue. Do large and small cars have different accident involvement rates and, if so, why? Some evidence indicates that small cars do have a higher involvement rate than large cars. The Highway Loss Data Institute (HLDI) studied first party claims and derived claim frequency per 100 insured vehicle years; they attempted to standardize the data by adjusting for driver age, under or over 25, and amount of deductible, $ 50 or $ 100. Results for 1972 and 1973 models as reported by the Insurance Institute for Highway Safety (IIHS) show that compact and intermediate class vehicles have a claim frequency approximately 20 percent greater than full-size care; and subcompact cars have a claim frequency 33 percent greater than full-size cars (Reference 1; page 3).

The Highway Safety Research Institute, University of Michigan, has published data indicating that small cars are over-involved in "out-of-control" single car accidents (Reference 2, page 11) and in collisions with other small cars (Reference 3, page 5). In part, this over-involvement has been attributed to average driver age with small cars having younger drivers. The overall evidence, when examined carefully, is not yet conclusive; and it is not unreasonable to assume a constant involvement rate regardless of size in any study to determine the effect of a reduction in average vehicle size.

The relationship between car weight and safety has been studied intensively on various samples, but such studies have not been extensive. As mentioned above, each investigator devises his own weight classes. O'Day, et/al, studied "small cars" with a licensing weight of 1,400 kilograms (3,100 pounds) or less and "large cars" with a licensing weight of 1,500 kilograms (3,300 pounds) or greater (the 100 kilogram gap was international to provide separation). They found (Reference 4, page 5) that the chance of a car being involved in an accident was not highly related to its weight, but once involved, the chance of injury in the car increases 2,5 percent for each 45 kilogram (100 pound) decrease in weight.

Mela studied a set of 32,980 two-car crashes which occurred in New York State during calendar years 1969-71. He divided the cars into five weight classes

(Reference 5, page 48-7). In adjusting and fitting the data he found implications that the driver's chance of serious injury increased or decreased by about 5 percent for each 45 kilogram (100 pound) increase or decrease in his car weight; his chance of serious injury increased or decreased approximately 2 percent for each 45 kilogram (100 pound) increase or decrease in the weight of the other car in the collision (Reference 6, page 48-8). Mela concluded that a shift in the U.S. passenger car population from its present weight distribution to one composed largely; i.e., 50 to 60 percent, of subcompact and compact cars with no cars exceeding 1,500 kilograms (3,250 pounds) could produce up to 25 percent more serious and fatal injuries. Interestingly, he found that doubling of current safety belt usage would enable this population of smaller cars to be used with about the same injury rate as now exists for today's heavier, mixed population (Reference 5, page 48-18).

Scott also investigated a New York State accident file and found that when the primary vehicle shipping weight is under 1,150 kilograms (2,500 pounds), the crash severity is essentially the same regardless of the weight of the secondary vehicle. This severity is two to three times that found in the case of a larger car (above 1,500 kilograms (3,250 pounds) striking another large car (Reference 7, page 13-15 and 13-22). He also found that belted drivers of cars in the 450 to 900 kilogram (1,000 to 1,999 pound) class have about the same percent of serious and fatal injuries as unbelted drivers of cars in the 1,500 to 1,800 kilogram (3,250 to 3,999 pound) class (Reference 6, page 13-16). These findings correspond well with those a Mela.

Campbell and Reinfurt studied accidents accurring in North Carolina in 1966 and 1968-71. They established an injury index with 100 as the average value. An index of 120 means 20 percent more frequent serious injury to a driver than average and, an index of 80 means 20 percent less frequent serious injury than average. In car vs, car crashes, the index chart crosses 100 at approximately 3,000 pounds for the two cases: (a) all injuries, and (b) serious and fatal injuries (Reference 7, page 21 and 22).

In later work, Campbell, O'Neill and Tingley studied crashes of 1970-73 model cars drividing them into five categories: full-size intermediate, compacts, subcompacts, and import cars. Their data show that smaller cars, including imports, tend to have twice as many single car, predominately ran-off-road, accidents as the combination of full-size and intermediate cars. This holds true for both belted and unbelted drivers (Reference 8, page 12-3). This supports the findings of the Highway Safety Research Institute mentioned above.

Using an index system similar to that described above, the data show that belted drivers in subcompact and compact cars have approximately the same chance of injury as unbelted drivers of intermediate and full-size cars (Reference 8, page 12-6).

The above findings indicate that injury levels become a problem if the curb weight of an automobile drops below 1,500 kilograms (3,200 pounds). This conclusion is based upon accident data and is, therefore, a measure of the capability of cars using present designs and manufacturing techniques.

Compounding the weight and safety problem is the tendency for vehicle safety requirements to increase vehicle weight; thus aggravating the fuel economy and emission problem. In reviewing Federal Motor Vehicle Safety Standards implemented in the United States over the past several years, we find that combined consumer protection and safety standards have increased the weight of an average car by about 118 kilograms (260 pounds). This, in turn, has resulted in a fuel economy penalty of about 3 percent. Further motor vehicle standards that have been issued but are not yet in effect may increase average vehicle weight by another 15 kilograms (34 pounds).

The connection between weight increases and future safety and consumer standards is not so clear. This is primarily because the effects of soft-nose bumpers and various other possible safety designs are as yet undefined. Reasonable estimates, however, indicate that weight increases of about

140 kilograms (300 pounds) for the average car may be required. This rather pessimistic prediction of weight increases from future standards is, of course, based on today's automotive engineering materials and technology. Automotive technology advances and the use of new materials or structural designs could greatly ameliorate the weight penalties of the upgraded vehicle safety that we need.

Aluminum and plastic are commonly mentioned material substitutes. Aluminum prices are increasing; aluminum production requires large amounts of energy; and there are valid questions as to the availability of aluminum in sufficient quantities. Recent unpublished findings under a Department of Transportation contract indicate that increasing aluminum usage from the present 37kilograms (81 pounds) per car to 91 kilograms (200 pounds) per car would require increasing the industry capacity by 15 percent. Such an increased use of aluminum could reduce car weight by about 55 kilograms (120 pounds). Plastics used in automobiles are largely petroleum products, so a major limitation on their use is self-evident.

Likely near-term substitutes are the various high strength low alloy (HSLA) steels. These steels have significant strength advantages, but require larger forming equipment as the punch forces must be higher. Another problem is variation in weldability from run-to-run and batch-to batch. An in-service problem exists because the thinner sections will be less tolerant of corrosion (Reference 9, pages 30-32). Recent unpublished findings under a Department of Transportation contract indicate that extensive use of HSLA steels could reduce the weight of a standard-size passenger car by 150 to 180 kilograms (300 to 400 pounds).

Increasing the use of aluminum and incorporating HSLA steels could conceivably reduce the weight of a standard-size car by 10 percent by 1979 or 1980. A similar reduction appears possible for intermediates; the reduction for the smaller size classes would be somewhat less. Such cars could represent a significant proportion of the automobile population by 1985. The effect of materials changes on injury rate may not be commensurate with the magnitude of the reduction in curb weight, because the weight of the playload is unchanged. Cars in the various size classes would have the same relative strength that they now have, but crash energy levels based upon weight at impact would be reduced by a smaller percentage than the reduction in curb weight.

Research Safety Vehicle (RSV)

In recognition of the continuing experimental and research needs concerning the motor vehicle as a total system, the United States has initiated an advanced state-of-the-art Research Safety Vehicle (RSV) Project as the logical next step in its Experimental Safety Vehicle Program mentioned earlier. This project takes special recognition of the projected transportation challenges of the 1980's, and is structured to address the problems of minimizing fuel consumption, controlling urban congestion and pollution, and maximizing resource conservation as well as safety. The initial proposed specifications stressed a maximum weight limit of 1,364 kilograms (3,000 pounds) for the RSV and were distributed to all participants at the Fourth International Technical Conference on Experimental Safety Vehicles held in Kyoto, Japan in March 1973. Requests for proposals were forwarded to all governments and manufacturers participating in the International ESV Program. Contract awards for Phase I, concept definition and specification development, were accomplished in January 1974. The Phase I participants, who will be competing for the design and fabrication phases to follow, are: AMF, Inc., Calspan Corporation, Ford Motor Company, Minicars, Inc., and Volkswagen.

In contrast to the original Full-Size Experimental Safety Vehicle (ESV) Program, the approach to the development of final specifications for the RSV will depend substantially on the technically decumented recommendations of the five Phase I contractors. In this respect, the program is attempting to establish firmly at the onset an agreed upon, realistic foundation for the subsequent design, fabrication and testing phases. The program will build on the engineering and research data base established by the initial ESV prototype developments and project these engineering solutions and concepts to the design of a 1,364 kilogram (3,000 pound) car for the 1980's.

The Memoranda of Understanding on ESV development and the exchange of technical information as a result of these memoranda certainly include the United States RSV Project. We expect RSV Phase I study results to be published in early 1975. As in the initial ESV Project, we fully intend to make all information generated during the RSV Project available to all international participants on as timely a basis as possible within the constraints of our contractual approach.

The initial ESV prototype development phase, begun in 1970, is drawing to a conclusion with the fabrication and testing of at least 20 experimental vehicles by 12 different manufacturers covering weight classes from below 1,000 to over 2,300 kilograms. Discussions are now in progress among the participating nations for meaningful follow-on projects. During the recent Fifth International Technical Conference on Experimental Safety Vehicles in London, these discussions centered on the possibility of broadening international cooperation to include research areas identified by the initial phase of the ESV Program as requiring additional research effort.

Conclusion

In summary, I should like to emphasize once again that in searching for improved automotive designs to control emissions and improve conservation of our fuel resources, we must also keep in mind the safety of the motoring public. In the past, many vehicle safety improvements have required rather severe penalties in terms of weight and, consequently, fuel economy. Developments in recent years have encouraged us in the hope of finding ways to substantially improve vehicle safety without incurring heavy weight penalties.

The total problem is too large and too important to be handled by one nation alone, and it is through conferences such as this one and the companion International Experimental Safety Vehicle Conferences that the full weight of the world's automotive technology resources can be brought to bear.

I am certainly encouraged by the advances in fuel economy and emissions control discussed and analyzed here this week. I trust that those of us in the safety community can contribute equally practical and effective solutions to our problem as well. The end result then would be a safe, economical, fuel efficient and clean automobile.

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Rapport soumi par la délégation française
par P. Dreyer

Au cours de ces 3 dernières années, le gouvernement français a distribué une somme de l'ordre de 6 millions de francs par an au titre d'une aide à la recherche sur la réduction de nuisances dues aux transports terrestres en site banal. Cette somme est grossièrement répartie entre la recherche sur la réduction de la pollution pour 60 % et la recherche sur la réduction du bruit pour 40 %. Il nous semble en effet que le bruit est une nuisance importante subie par la plupart des citadins et plus particulièrement les riverains des voies rapides urbaines. Le meilleur moyen de réduire ce bruit est certainement de le faire à la source, c'est à dire au niveau du véhicule.C'est pourquoi un effort particulier est fait dans ce domaine.

La procédure d'allocation de ressources est assez simple : un certain nombre d'axes de recherche sont définis et proposés à l'industrie, aux bureaux d'études et autres instituts de recherche. Un comité d'experts examine ensuite les projets de recherche envoyés en retour et choisit ceux qui seront financés en fonction de l'enveloppe budgétaire et de l'intérêt des projets. Les contrats ont des durées de 1 à 3 ans et portent sur des sommes variant de 100 000 à 900 000 francs.

Sur les fonds alloués à la pollution, une partie a été consacrée l'an dernier à ce que les anglo saxons appelent "Technology Assessment", et que nous traduisons par "evaluation d'options techniques". Il était important en effet de faire le point des connaissances sur les nouveaux systèmes de propulsion et d'essayer de dégager les conséquences générales, économiques aussi bien que techniques, de l'introduction de ceux-ci.

Trois études sont en cours ou sur le point de démarrer pour évaluer:

- les moteurs thermiques, conventionnels ou non
- les systèmes hybrides à accumulation électrique
- les systèmes de propulsion entièrement électriques.

Les résultats de ces études devraient être connus à la fin de 1975.

A ces études d'évaluation d'options techniques peuvent se rattacher deux études qui vont être financées sur les hydrures métalliques.

J'ai précédemment mentionné l'existence d'un certain nombre de critères pur le choix des projets à retenir. Parmi ceux-ci figurent cette année avec un poids tout particulier les considérations énergétiques lorsqu'un nouveau dispositif ou une modification du moteur conventionnel est proposée pour réduire le bruit sur la pollution, il faut veiller, si possible, à ce qu'il n'acccroisse pas la consommation de carburant. Il est même préférable qu'il puisse la réduire.

Ces trois domaines : la réduction du bruit, la réduction de la pollution et la réduction de la consommation sont bien sûr souvent étroitement imbriqués, surtout si l'on s'attaque au moteur lui-même et il arrive qu'une étude puisse nous être proposée soit au titre de la réduction du bruit, soit au titre de la réduction de la pollution.

Ces financements étant de création récente, la plupart des études entreprises ne sont pas encore terminées ou, si elles le sont, nous n'en avons eu les rapports finals que récemment et il me serait donc impossible de vous en faire ici une synthèse rapide. Je me contenterai donc d'énoncer les champs de recherche pour lesquels nous avons distribué des subventions, sans mentionner les résultats déjà acquis.

Je ne vous donnerai pas non plus une liste exhaustive des contrats en cours de déroulement ou qui vont bientôt demarrer ; il y a environ 25 contrats au titre de la réduction de la pollution et une quinzain au titre de la réduction du bruit ; les listes peuvent être demandées au Centre d'Evaluation et de Recherche des Nuisances de l'I.R.T. au 109, avenue Salvador Allende - 69 500 - BRON.

En ce qui concerne la pollution tout d'abord, les études peuvent se répartir en plusieurs catégories:

- des recherches que nous pourrions appeler fondamentales qui tendent à mettre en évidence l'influence des paramétres d'un moteur sur les émissions de polluants. On pourrait aussi y rattacher deux études sur les moteurs à préchambre de combustion et une recherche sur la caractérisation des odeurs émises par les moteurs Diesel. Vous savez en effet, qu'un des points faibles du moteur Diesel, qui par ailleurs semble intéressant par son très bon rendement, est qu'il émet des gaz d'échappement aux odeurs jugées désagréables. Il convient donc de les diminuer.

- une autre groupe de recherche concerne l'alimentation du moteur en carburant et différentes études traitent soit de l'amélioration des carburateurs, soit de la mise au point de systèmes d'injection. Pourraient s'y rattacher des études sur une amélioration de la distribution ou de l'allumage.

- un dernier groupe enfin, pourrait rassembler toutes les recherches sur la réduction de la pollution par l'utilisation de catalyseurs.

On voit à cette description sommaire que si certaines recherches concernent des dispositifs qui pourraient être utilisés à court ou moyen terme, comme l'utilisation de pots catalytiques, d'autres répondent beaucoup plus à des préoccupations à long terme, à savoir: si l'on conserve le moteur à combustion interne pour la propulsion des véhicules terrestres, comment pourrait-on les modifier pour que leurs émissions de bruit, de gaz toxiques et d'odeurs deviennent acceptables. Il est bien évident en effet que si des modifications importantes dans la conception des moteurs sont nécessaires pour arriver à ce résultat, il faudra attendre un certain nombre d'années pour qu'elles apparaissent sur des moteurs produits en série.

Pour ce qui est des recherches sur le bruit, on peut aussi diviser les recherches en deux grandes familles selon qu'elles concernent le long terme ou le court terme.

Pour le long terme, on retrouve des études sur l'influence des paramètres du moteur sur le bruit émis. Des études sont en cours ou vont être entreprises sur les bruits des moteurs Diesel, des moteurs à allumage commandé et des moteurs deux temps. Des études seront aussi entreprises sur les bruits de pneumatiques, et une étude théorique qui vient de s'achever sur les bruits de ventilateur devrait se prolonger l'an prochain.

Pour le court terme, des études ont été effectuées sur la réduction du bruit d'un autobus et d'un véhicule de tourisme en enfermant leurs moteurs dans une cocon, méthode qui commence à être bien connue. D'autres études concernent la réduction du bruit de l'admission ou de l'échappement ou des vibrations de pièces particulières.

Ce programme de recherches, que je vous ai présenté en quelques mots peut donner l'impression d'une incertitude quant aux éléments sur lesquels agir. Cette impression n'est pas complément dénuée de fondement car pour la pollution, et peut être plus encore pour le bruit, les connaissances en France ne remontent pas à de nombreuses années et sont encore fragmentaires, il convient avant tout de les préciser.

Report of the Delegation of the Netherlands
by L.C. van Beckhoven

The main subject of the Dutch sponsorship programme is the Stirling engine which has been under development by the Philips Laboratories for about 35 years. Only the last few years it was realized that this engine has very large potential as a low pollution power source. The use of a Stirling engine in a passenger car is being studied already. Further plans regard the use of Stirling engines in city buses. Here of course, emissions and noise are of primary importance as well as good energy conversion efficiency.

As a full evaluation will be a fairly lengthy and costly operation, we have considered it desirable to first have a feasibility study. This study is scheduled to take one year; it will decide on the design parameters for this particular application and so in some details of construction, it will give a first estimate of exploitation costs as compared with a Diesel-powered bus and it also will submit a plan for the second phase of the evaluation.

The Dutch government is going to support this study to the amount of 850.000,- Dutch Guilders.

On the basis of this study we will have to decide whether we will continue to support this programme or not.

If we do, support needed is estimated at 7 to 10^6 Dutch guilders per year during a number of years.

During this phase II a small number of city buses will be equipped with Stirling engines and operated and evaluated under practical conditions.

Now, I am certain other R and D activities in the LPPS-field are going on in the Netherlands or are being prepared like a study of small motorcycle emissions and a programme on cleaner and quiter Diesel-engined buses.

However,I have no further data on government support with me. This then concludes my presentation.

Thank you, mr. Chairmen.

Report of the Swedish Delegation
by [illegible]

In Sweden the three Government Departments of Industry (DOI), Transportation (DOT) and Agriculture (DOA) are all involved in LPPSD. The EPA-equivalent - (Naturvårdsverket in Swedish) - comes under the DoA - Agriculture - and is responsible for formulating the overall environmental protection goals, to implement regulations and perform control of pollution. However, the responsibility for Road vehicle Pollution Measurements & Control including noise regulations lies with the Dept. of Transportation (DoT).

Furthermore, the Government - supported technical R & D on LPPSD is handled by my agency STU, which covers almost all major technical R & D programs, under the Dept. of Industry. Now, as regards the national effort and budgets - in order to give a realistic perspective, I would like to start by saying that STU handles a major part but not all of Gov't R & D funds in Science & Technology (Natural Sciences), namely ca. $ 25 mill per year - which is somewhat less than 10 % of the total national R & D effort in that area. These 25 mill. dollars are distributed into ten major Sectors of Need, including the following four, which include sectors of LPPSD, namely:

1. Energetics (new fuels, electric batteries, fuel cells)
2. Materials (e.g. steel alloys, composites, ceramics)
3. Transportation (Road Vehicles & Power Systems, LPPSD, tracked vehicles etc.)
4. Environm. Protect. Technology (Pollution control technology & hardware, Traffic noise suppression, vehicles)

The major LPPS-funding at present comes within sector 3. Transportation, where the annual LPPS-budget since 1970 has been ca. 0.5 mill. dollar with more than 1 mill. dollars allocated to major programs in each of Stirling and Gas Turbine developments, and lesser funds to Otto/Diesel and electric power system programs.

As regards the STU-supported Stirling and Gas Turbine programs both are now going ahead largely on their own on corporate funds, the United Stirling program in collaboration with the Ford Motor Co and United Turbine by financial support from Volvo.
STU-support continues at some 100-160 thousand dollar level for each of these two programs this fiscal year 1974/75.

The Otto/Diesel engine R & D programs - ca. 100.000 dollars annually-are largely handled by professor Lars Collin at Chalmer's Institute of Technology (CTH), Göteborg and include several important subprograms on LP (low-pollution) developments, concerning thermodynamic analysis, ignition parameters, induction and exhaust treatments etc.

Electrical Power System R & D is supported both in basic battery development

- SU - Swedish Development Co. - Iron Air - Battery promising three times the energy density of lead battery

and in

- electric control systems for light duty vehicles
- motorbike - regenerative brake energy recovery with thyristor control and with 20 - 25 % range increase vs conventional
- contract extended to light city automobile system

Now, we also perform studies in
LPPSD - evaluation criteria
aiming at - overall STU R & D Planning
- evaluation of PP-contract proposals.

Finally I shall mention our new Traffic Noise/Vehicle Noise suppression R & D efforts, based on a Gov't study of issues & regulation proposals which has just come out - to be reviewed Febr. 1975 - likely to result in legislation 1976-1977.

Summary of 1974/75 FY STU programs, $ 720.000, see attached table.

STU - SUPPORTED R & D PROGRAMMES ON LPPSD + VEHICLE NOISE SUPPRESSION

Programme	Annual Funding Mill. US $, 1974/75
1. OTTO/DIESEL DEVELOPMENT Prof. Collin, CTH (+ other)	0.110
2. STIRLING - Critical Subsystems Development (Phase 3) United Stirling	0.160
3. BRAYTON - Gas Turbines United Turbine	0.120
4. RANKINE (SAAB-Proprietary)	-
5. ELECTRO-CHEMICAL - Batteries/Systems	
5.1 Iron-Air battery (final phase) Swedish Development Co	0.070
5.2 Motor-bike, regenerative control	0.050
5.3 El-control system survey	0.100
6. LPPSD Evaluation Criteria Study-Phase 1	0.030
7. Road Vehicle Noise Suppression - Phase 1 (3 projects)	0.080
1 - 7. TOTAL Current STU:	0.720 million

Report of the U.K. Delegation
by G. Donald

1. The Quite Heavy Goods Vehicle

Aim: The aim of the project is to demonstrate the feasibility of manufacturing heavy commercial vehicles with low noise emission at an economic price. The target noise level is 80dB(A) under all operating conditions. The end product will be two prototype vehicles built by industry to the Department of the Environment (DoE) sponsored design.

Sponsor: The project is sponsored by DoE with industry participating at the development stage, the project is co-ordinated by TRRL.

The initial budget for the work was £ 500,000 this has esculated within DoE is £ 750,000.

The project is in two phases;

a) research which includes the basic design of suitable enginge, exhaust/inlet systems, cooling system and cab interior. Computer techniques are being used wherever possible and in particular in the design of the exhaust system; and

b) The production of the demonstration vehicles by the motor industry.

Time Scales: The research phase should be completed by the end of 1975. The demonstration vehicles should be on the road by 1977.

Progress: One experimental engine is running on a test-bed at the present time and will be installed in a vehicle early 1975.

A computer designed exhaust system has been installed in a test vehicle and is meeting the target noise levels set for the exhaust system. Two cooling systems are being investigated, one roof mounted and the other of more conventional design.

A second design of engine is being constructed and will be running in test-bed form during the Spring of 1975 and will be installed in a vehicle by mid 1975 for road tests. Present indications are that work on engine, transmission and exhaust noise will be successful. The limiting factor is the noise produced by the Tyre/road surface interaction. Whilst our target can be achieved under dry road conditions it may not be possible to attain the target on wet roads. It may be that a solution can be found in a combination of tyre and road design.

An extension of the QHGV project is being considered to include light commercial vehicles equipped with diesel engines. The present requirements to conserve energy resources has focussed attention on the use of diesel engines in a lighter range of vehicles than has been the custom up to now. Such vehicles present a different set of design problems to those of the QHGV. No decision has been taken to proceed with this work.

2. Sodium/Sulphur Batteries

Aim: To develop a practical battery.

The sodium/sulphur battery is considered to be the most promising alternative to the lead-acid battery. The sodium/sulphur battery will have a better performance (approx. a factor of 10 in energy density) than the lead-acid battery and its constituent materials are found in abundance.

Sponsors: DoE are funding British Rail for the development of a battery suitable for use in a rail-car. DoE investment in the project will be about £ 200,000 per year for 3 years. It is expected that one battery will be installed in a rail-car by 1976. DofI are sponsoring further work at UKAE Harwell on the development of sodium/sulphur batteries at a cost of £ 100,000 per year.

The nationalised Electricity Council have produced a small experimental sodium/sulphur battery capable of providing the power required to operate a 30 cwt van. The Electricity Council in conjunction with Chloride Limited are carrying out a separate research programme orientated towards the use of sodium/sulphur batteries in road vehicles.

Time Scales: Current estimates suggest that if programmes keep to schedule prototype production batteries may be available in 5 years and this type of battery may be in limited commercial use in 10 years.

Report of the Delegation of the Federal Republic of Germany
by D. Frenzel, Federal Ministry for Research and Technology
Research and Development in the sector of "Vehicle and Traffic Technology"

Since 1950, the share taken up by private means of transport in the total volume of traffic has increased from 35 % to 73 %. These firgures show what great importance the motor vehicle has in our society, which is dependent on mobility. The motor vehicle constitutes a major prerequisite for the high national economic efficiency of our society. The automobile must also be regarded as a factor in the quality of life which the individual citizen would not like to have to go without, on account of the independence made possible by the possession of one's own private car. According to conservative estimates, the share taken up by private means of transport in the total volume of traffic will continue to increase, meaning that the motor vehicle will be indispensable for the foreseeable future.

Although the automobile has undisputed advantages, it also has considerable disadvantages such as

constituting a source of environmental pollution,
and a threat to life, health and property,
taking up too much space on roads and
consuming a great amount of primary energy.

Coping with the above-mentioned disadvantages is to be regarded as one of our most urgent tasks. In addition, there is the fact that natural limits will be set within the foreseeable future to the use of the car as a private means of transport owing to the shortage and increasing price of the primary energy required for motor vehicle power systems.

Realizing these problems raised by private means of transport, the Federal Minister for Research and Technology has drawn up a promotion programme for research and development in the sector of "Vehicle and Traffic Technology", thus emphasizing the direct responsibility borne also by the government in this field.

Situation and Objectives

The sharp increase in the use of private means of transport has resulted in problems which cannot be solved by organizational and legislative measures alone. In addition, extensive technological research and development activities must be introduced. To some degree, requirements exceed the capabilities of industry and science, and, in view of the importance of motor vehicle traffic for the national economy, the government is also responsible for coordinating both necessary and risky research and development projects, and to support these by systematic promotion measures.

Diagram 1 shows a concise list of the reasons which have led to government promotion in the sector of "Vehicle and Traffic Technology". No conclusions as to priorities should, however, be drawn from the order in which reasons are presented in the diagram. Priorities are first and foremost influenced by developments in both politics and the world economy, as has been demonstrated by the development in the sector of crude oil during the past 2 years.

Mobility enjoyed by the possession of private means of transport can be preserved only if the utilization of energy and the employment of resources are improved. All measures designed to produce motor vehicles with low-energy requirements must, however, not fail to give consideration to the necessity for greater safety for health, life and property, as well as for more orientation to the preservation of the environment, and for long-term deliberations as to the role to be assumed by motor vehicle traffic in the total traffic volume with the optimal cost/utilization ratio for society and the national economy.

Programme and Activities

The entire programme for the promotion of research and technological development in the sector of "Vehicle and Traffic Technology" can be subdivided under the following activities:

- Preparatory studies with regard to planning and the coordination of government promotion measures,
- Power systems,
- Fuel and other sources of energy.

The two last-named activities deal with the problems to be discussed during this Symposium, and will therefore be debated in detail below.

- Chassis and superstructure
- Motor vehicle equipment
- Traffic routes
- Installations and facilities

Within the framework of this presentation, reference is made to these fields only for the sake of completeness, since they no longer touch on the range of topics to be discussed at this Symposium. On the other hand, however, they constitute sectors of work for promotion in the field of "Vehicle and Traffic Technology".

Power Systems

Owing to the large number of vehicles equipped with Otto cycle or Diesel engines and also by virtue of existing production plants and the infrastructure, it can be expected that both Otto and Diesel engines will be installed in motor vehicles for a long time yet, and that the chances in the immediate future for new-type power systems of winning an important share of the market are only modest.

Following development over several decades, pursued at great expense, conventional engines have reached a technical level which would appear to suggest that it would be expedient to give priority to work aimed at improving both orientation to the preservation of the environment and economic utilization. Moreover, the attainment of these goals is expected to require less time than the designing of new-type power systems. The promotion programme drawn up by the Federal Minister for Research and Technology accordingly takes these facts into account. They are also reflected in the "Power Systems" structural plan (Diagram 2). It can be seen that the major share of important secondary activities is concerned with the problems arising in the sector of Otto and Diesel engines.

Where Otto cycle engines are concerned, attempts are being made to reduce the amount of noxious exhaust emissions chiefly by improving the charge formation and ignition, and also by exhaust aftertreatment. Efforts must also be made to reduce noxious exhaust elements in the case of Diesel engines, too, which are already known to have considerable low-polluting properties. In particular, emissions in the form of soot and smells are to be reduced. As a result of transferring the features of Diesel engines to the Otto cycle engine, the stratified charge system was developed. This system has already yielded promising results with regard to exhaust emissions and economic utilization.

Since, on a long-term basis, consideration might very well be given to the substitution of new-type designs, such as engines with internal combustion, motor vehicle gas turbines, hybrid power systems, rotary cylinder engines, Stirling engines, etc., for existing power systems, research work on such new-type power systems is being promoted.

Fuel and other sources of energy

Diagram 3 shows how the activities carried out under the heading of "Fuel and other sources of energy" are grouped. Owing to the fact that fossil fuel for motor vehicles will become increasingly scarce in the foreseeable future, research activities are primarily concerned with the fields of "Synthetic fuel", "Mechanical energy-storage systems" and "electric energy-storage systems".

In the sector of "Synthetic fuel", the Federal Ministry for Research and Technology requested that a study be prepared with the aim of gaining information as to the availability, manufacturing and utilization possibilities of methanol and hydrogen as alternative fuels for conventional motor vehicle power systems, and also to show what further advanced research and development activities must still be carried out. This study has been drawn up in team work by 15 different institutions. A limited number of copies are available for your perusal.

Summary

The motor vehicle is one of the most important means of transport today, and will remain so for the foreseeable future. Its undisputed advantages are, however, in view of the technical systems normally used today and the way in which these systems are used, offset by increasingly serious disadvantages. The strains placed on the environment achieve quite alarming proportions to some extent, and compel us to establish legal regulations in order to limit emissions.
The necessity of using resources economically over a long-term period - a topical case in point is the diminishing supply of conventional sources of fuel - requires that new developments be found. Organizational and technological changes in strategy are made necessary to deal with the shortcomings in the traffic situation and settlement policy.

In this respect, and appeal is made to the sense of responsibility and cooperation on the part of the government that it participate in planning and contribute to dealing with crucial issues. Within the framework of planning future supplies and as an aid to selfhelp, the government draws up measures for promoting sectors of research and development which involve risks.

To date, DM 8.9 million were provided in 1974 by the Federal Ministry for Research and Technology in the sector of "Vehicle and Traffic Technology". In general, this was effected by assuming 50 % of project costs. Despite the necessary economies which must be made by the government, adequate promotion funds must continue to be provided for this field.

In 1975, promotion funds are to be increased to DM 9.8 million. It is envisaged that activities already under way will be continued after 1975 to an intensified extent.

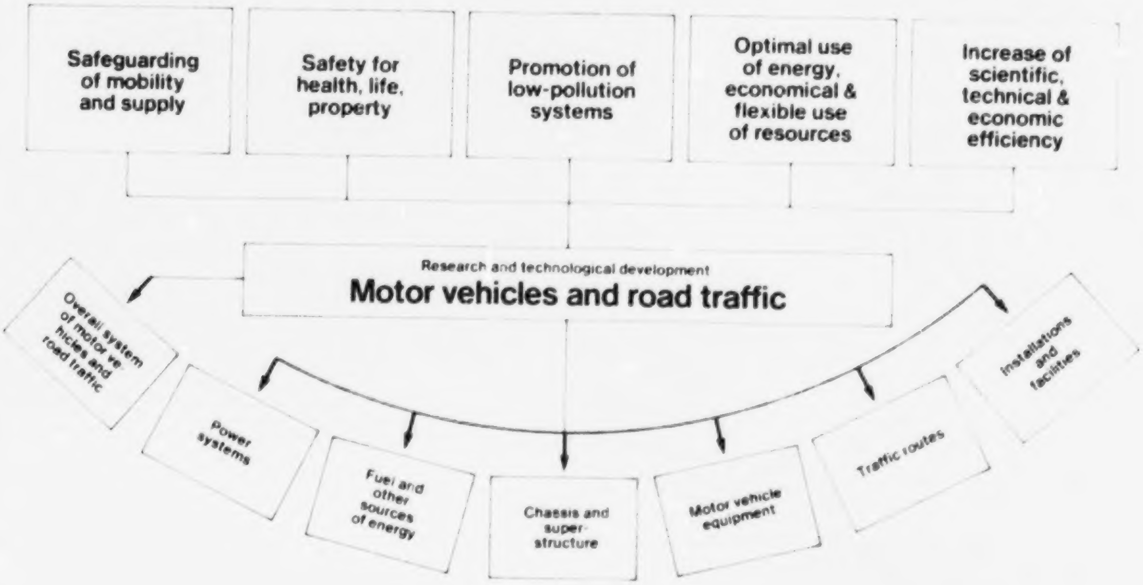
Safeguarding of mobility and supply
Safety for health, life, property
Promotion of low-pollution systems
Optimal use of energy, economical & flexible use of resources
Increase of scientific, technical & economic efficiency
Research and technological development
Motor vehicles and road traffic
Overall system of motor vehicles and road traffic
Power systems
Fuel and other sources of energy
Chassis and superstructure
Motor vehicle equipment
Traffic routes
Installations and facilities

Diagram 1

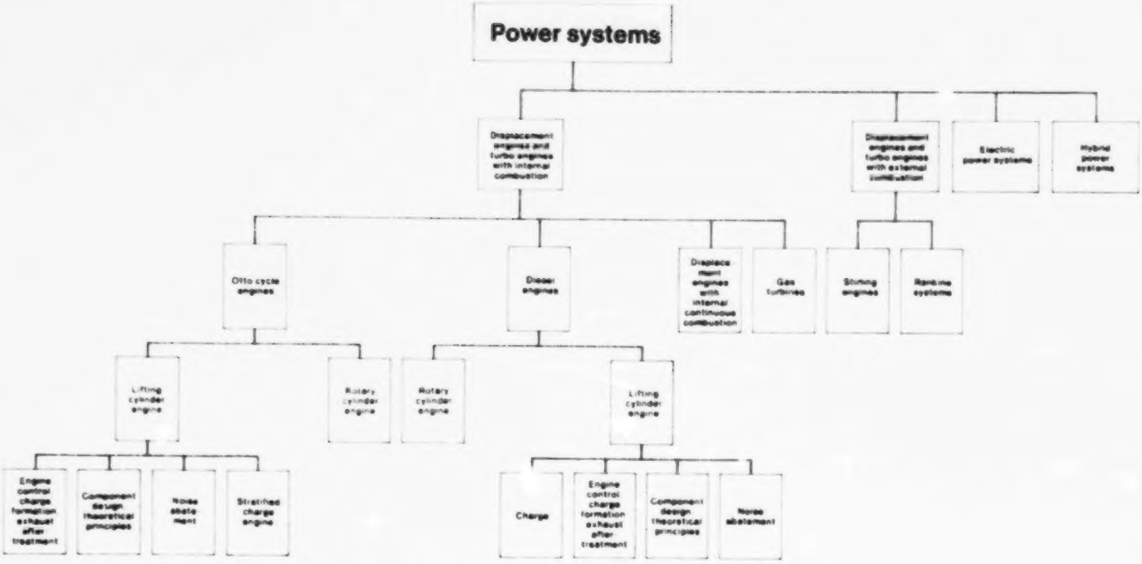
Power systems
Displacement engines and turbo engines with internal combustion
Displacement engines and turbo engines with external combustion
Electric power systems
Hybrid power systems
Otto cycle engines
Diesel engines
Displacement engines with internal continuous combustion
Gas turbines
Stirling engines
Rankine systems
Lifting cylinder engine
Rotary cylinder engine
Rotary cylinder engine
Lifting cylinder engine
Engine control charge formation exhaust after treatment
Component design theoretical principles
Noise abatement
Stratified charge engine
Charge
Engine control charge formation exhaust after treatment
Component design theoretical principles
Noise abatement

Diagram 2

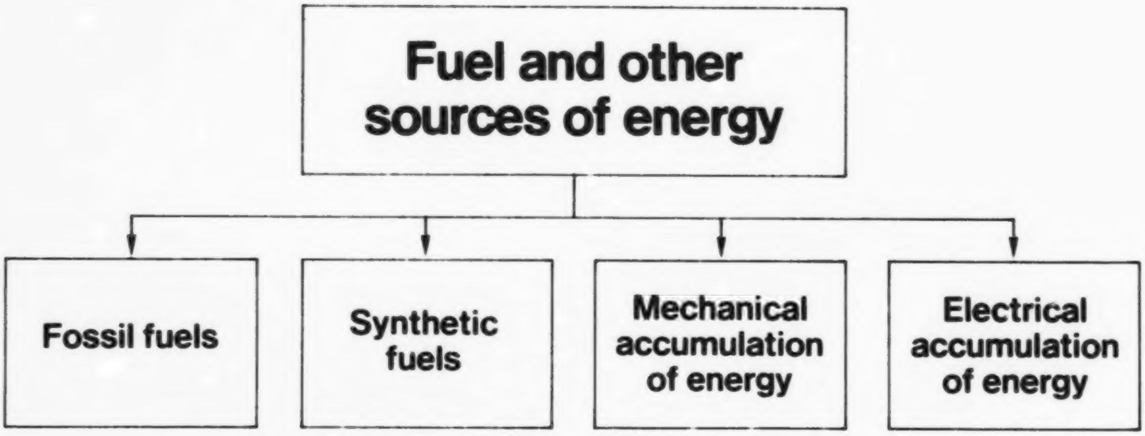
Fuel and other sources of energy
Fossil fuels
Synthetic fuels
Mechanical accumulation of energy
Electrical accumulation of energy

Diagram 3

Statement of the Delegation of the Federal Republic of Germany by Ministerialrat H.L. Dreißigacker, Federal Ministry of the Interior, Bonn

The Traffic-Emissions-Program, which will be explained in detail by Mr. Neubaur in the second part of this report, shall provide the scientific and technical basis for legislation in the following areas:

Regulation	Time schedule for passing into law for the Federal Republic of Germany
2nd stage of reduction of exhaust emissions for vehicles with gasoline fueled engines (CO: 20 % less, CH: 15 % less)	October 1, 1975
Adaption of the test procedure type I to the progress of technology (standards for NO_x)	October 1, 1976
Limitation of evaporative emissions from fuel tanks and carburetors/fuel injection systems	October 1, 1976
Limitation of evaporative emissions during filling automobile fuel tanks	Will not be persued for the next time because of changed concept
Control of exhaust emissions from vehicles in use	October 1, 1977

3rd stage of reduction of exhaust emissions from vehicles with gasoline fueled engines (CO: 58% less, CH: 72% less, NO_x: average in 1972), equal to 10% of the average emissions in 1969	October 1, 1980
Limitation of emissions of cancerogenetic hydrocarbons	Later than 1980
Limitation of NO_x-emissions from vehicles with diesel engines	October 1, 1980
Limitation of odorous emissions from vehicles with diesel engines	October 1, 1980

Legislation in the Federal Republic of Germany will be in accordance with the accepted specific guiding rules of the european community. Standards which will be effective in 1980, will have to be communicated to the industry within 1975 because of the time needed to transfer the results of research and development to series production.

The Traffic-Emissions-Program of the Federal Ministry of the Interior of the Federal Republic of Germany by H.P. Neubaur, Dornier System GmbH, Friedrichshafen

Regulation and laws in the Federal Republic of Germany affecting the reduction of automotive emissions are a substantial part of an extensive environmental program of the Federal Government. In order to find efficient techniques for measuring and testing and to induce economical solutions for the reduction of emissions, in early years several projects of research and development had been sponsered by the ministry and conducted by some competent institutes of universities in the country. From this beginning about 1968 up to 1970 the increase of activities in this area lead to a number of about 60 projects, running, planned and finished ones all together. This expansion required to share at the program some other kinds of institutes like the Federal Institute for Testing Materials (Bundesanstalt für Materialprüfung), the Technical Associations for Inspection at Cologne and Essen (Technischer Überwachungsverein Rheinland/Köln and Rheinisch-Westfälischer Technischer Überwachungsverein/Essen) - the latter one at the same time is the official board for certification of vehicle emission tests - as well as the industry, especially the automotive industry. For the time to come it is intended to sponser even more projects for the development of hardware and for this purpose to use the immense knowhow of the automotive industry.

Nevertheless the automotive industry get nowadays is an important participant in the federal program. For example some years ago there was launched an institution called program-steering-group, assembling in nonpublic hearings for several times a year in order

- to discuss the aims of the program,
- to give an expert's opinion to the running projects,
- to recommend or set priorities for new projects.

The members of the group are:

- The program management, i.e. the Federal Ministry of the Interior and the Federal Environmental Agency (Umweltbundesamt),

- The Federal Ministry of Transportation,

- the Federal Ministry for Research and Technology,

- the Union for Research of Combustion Engines (Forschungsvereinigung Verbrennungskraftmaschinen), a foundation of about all german car manufacturers,

- the Society of German Engineers (Verein Deutscher Ingenieure/ VDI), represented by the chairmen of the two working groups "exhaust gases of gasoline fueled engines" and "exhaust gases of diesel engines", both representatives at the same time are in leading position in the automotive industry,

- one representative of the research center of the largest german car manufacturer.

The composition of this group demonstrates the intensive participation of the industry at the peak of the program, but at the base there is another sharing of the industry:

- for several projects, done at the institutes of universities, there exist different groups of consultants, which themselves are working in the industry at similar problems,

- the automotive industry formally is asked for its opinion to the results of the projects just finished.

The cooperation at all can be judged to be very efficient and it has served to induce an atmosphere of confidence between the board preparing legislation and the industry afflicted by the laws.

The Traffic-Emissions-Program itself can be devided into seven thematic areas, which are subdivided again:

1) Planning, coordination and integration
    - planning
    - project control
    - superior studies
    - national coordination
    - international coordination
2) Technique for measuring and testing
    - measuring and testing procedures
    - permission and control of operation
    - analysis of datas
3) Automotive engine modifications
    - modifications for gasoline fueled engines
    - modifications for diesel engines
4) Automotive exhaust gas treatment
    - exhaust gas treatment for gasoline fueled engines
    - exhaust gas treatment for diesel engines
5) Influence of fuel
    - gasoline
    - diesel fuel
    - gaseous fuels
6) Non-automotive vehicles
    - railroad vehicles
    - aircrafts
    - vessels
    - factory traffic
7) Pilot systems
    - pilot systems

Each of these areas ordinarily contents several projects, some of them had been reported on during this symposium. The financial budget of the program concerning the ministry sponsering up to 100 % of the costs of some projects is about DM 4.500.000,-. The Association for Research of Combustion Engines adds another DM 400.000,- to the program. The projects yet finished had afforded again about DM 5.000.000,-. All these numbers are the summary of costs of several years according to the different durations of the individual projects.

Official Delegations

Délégations Officielles

Offizielle Delegationen

UNITED STATES OF AMERICA (Pilot Nation)

STRELOW, Roger (Head of Delegation)
Assistant Administrator for Air and Waste Management, Environmental Protection Agency

GREEN, Fitzhugh
Associate Administrator, Environmental Protection Agency

STORK, Eric O.
Deputy Assistant Administrator for Mobile Source, Air Pollution Control, Environmental Protection Agency

BROGAN, John J.
Director, Alternative Automotive Power Systems Division, Environmental Protection Agency

THUR, George M.
Chief, Power Systems Development Branch, Alternative Automotive Power Systems Division, Environmental Protection Agency

BARBER, Kenneth
Engineer, Power Systems Development Branch, Alternative Automotive Power Systems Division, Environmental Protection Agency

SEBESTYN, Thomas
Manager, Gas Turbine Section, Alternative Automotive Power Systems Division, Environmental Protection Agency

MYERS, Nancy S.
International Activities Coordinator, Office of Air and Waste Management, Environmental Protection Agency

LUDWIG, John H.
Dr., Consultant, Environmental Protection Agency

ESPOSITO, Vincent J.
Director of Vehicle Safety Research, Department of Transportation

GORUM, Alvin E.
Dr., Director, US Army Materials and Mechanics Research Center

LENOE, Edward
Dr., Chief, Mechanics Materials Division, US Army Materials and Mechanics Research Center

KATZ, Robert
Dr., Chief, Ceramics Research Division, US Army Materials and Mechanics Research Center

BURKE, John J.
Dr., Associate Director for Plans and Programs, US Army Materials and Mechanics Research Center

CANADA

GULLON, A.C.
Chief, Mobile Sources Division, Abatement and Compliance Branch, Air Pollution Control Directorate, Environmental Protection Service

GREAT BRITAIN

DONALD, George (Head of Delegation)
Civil Servant, Department of the Environment

PALMER, Robert John
Civil Servant, Department of the Environment

TYRRELL, Edward
Commander (Rn retired), Department of Industry

FRANCE

GAUVIN (head of Delegation)
Ingenieur des Mines, Ministère de l'Equipement

QUILICI
Conseiller Technique pour les Affaires Automobiles, Ministère de l'Industrie, du Commerce et de l'Artisanat

LAMURE
Centre de Recherche de l'Institut de Recherche des Transports

ITALY

OPPORTUNO, Vincenzo (Head of Delegation)
Ministero Transporti

ALPESTRI, Carlo
Ministero Transporti

NETHERLANDS

KUIPERBAK, Johan George (Head of Delegation)
Ir., Director of the State Office of Road Traffic, Ministry of Transport and Public Works

BECKHOVEN, van, Leon Christiaan
Ir., Ministerie van Volksgezondheid en Milieuhygiene

WEIDE, van der, Jouke
Ir., Instituut voor Wegtransportmiddelen TNO

TIEDEMA, Pier
Dipl.-Ing., Instituut voor Wegtransportmiddelen TNO

SWEDEN

LJUNGSTRÖM, Olle (Head of Delegation)
Dr., Swedish Board for Technical Development

COLLIN, Lars
Prof., Institutionen för Förbränningsmotorteknik, Chalmers Tekniska Högskola

HÄRDEN, Carl Gustaf Jan
Ingenjör, Swedish National Development

HUGOSSON, Sven
Chief Engineer, Swedish National Development

FEDERAL REPUBLIC OF GERMANY

MENKE-GLÜCKERT, P. (Head of Delegation)
Ministerialdirigent, Bundesminsterium des Innern

FRENZEL, Dietmar (Head of Delegation)
Dr., Regierungsdirektor, Bundesministerium für Forschung und Technologie

BANDEL, Jürgen
Dr.-Ing., Oberregierungsrat, Bundesministerium für Forschung und Technologie

BONK, Rudolf
Ministerialrat, Bundesministerium für Verkehr

BURCHARD, D.
Regierungsdirektor, Bundesministerium für Wirtschaft

DREISSIGACKER, Hans-Ludwig
    Ministerialrat, Bundesministerium des Innern

HARTMANN, Dietrich
    Dr.-Ing., Vizepräsident, Umweltbundesamt

List of Participants
Liste des Participants
Teilnehmerverzeichnis

ABDEL-WAHAB, Mustafa, Dipl.-Ing., Technisches Überwachungsamt, Darmstadt, D

ABIDIN, Anwar, Dr.-Ing., Institut für Landverkehrsmittel, Berlin, D

ABRÖLL, Manfred, Europ. Honda Motor Trading, Offenbach, D

ABTHOFF, Jörg, Dr., Daimler-Benz AG, Stuttgart, D

ADOMEIT, Gerhard, Prof. Dr.-Ing., Institut für Thermo- und Fluiddynamik, Technische Universität Berlin, Berlin, D

ADT, Robert R., Associate Professor, University of Miami, Coral Gables, USA

ALBRECHT, Helmut, Dipl.-Ing., Daimler-Benz AG, Stuttgart, D

ALPESTRI, Carlo, Eng., Ministero Transporti, Roma, I

AMSTEL, van, Gysbrecht, Dipl.-Ing., van Doorne's Automobielfabrieken B.V. - DAF, Eindhoven, NL

ANISITS, Ferenc, Dr.-Ing., Saurer AG, Arbon, CH

ARMSTRONG, Marshall, Assistant General Manager, Thermo Electron Corporation, Waltham (Mass.), USA

ASLANDER, Olle, Head of Sub-Division, Environment Protection Board, Solna, S

ASSELMAN, George, Dipl.-Ing., Philips Research Lab., Eindhoven, NL

ASTON, G.H.R., BP Research Centre, Sunbury, GB

BACHLE, Carl F., Consultant, Grosse Point Farms (Mich.), USA

BACHSCHMID, Reiner, Dipl.-Ing., Daimler-Benz AG, Stuttgart, D

BACKHAUS, Herbert, Dr., Geschäftsführer, Natural Gas Service Deutschland GmbH, Remagen-Rolandseck, D

BÄUMLER, Hermann, H. Pierburg KG, Neuss, D

BANDEL, Jürgen, Dr.-Ing., Oberregierungsrat, Bundesministerium für Forschung und Technologie, Bonn, D

BARBER, Kenneth, Engineer, Power Systems Development Branch, Alternative Automotive Power Systems Division, Environmental Protection Agency, Ann Arbor (Mich.), USA

BARDENBACHER, Rolf, Dipl.-Ing., Siemens AG, Erlangen, D

BARNER, Klaus-H., Dipl.-Ing., Oberregierungsbaurat, Bundeswehrbeschaffungsstelle Koblenz, Erprobungsstelle Trier, D

BARRETT, Albert, Sr. Tech., General Motors, Warren (Mich.), USA

BARTELS, Theo, Ing., Forschungslabor BK-Gas, Barneveld, NL

BARTHEL, Friedhelm, Secrétaire Général Adjoint, Comité des Constructeurs d'Automobiles du Marché Commun, Bruxelles, B

BARTSCH, Hans-Joachim, Dipl.-Ing., Institut für Kraftfahrwesen, Technische Hochschule Aachen, Aachen, D

BARTMÄ, Fritz, Dr. techn., Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt e.V., Stuttgart, D

BARZEN, Th., Bereichsleiter, Ford-Werke AG, Köln, D

BASSEWITZ, Graf, Georg Werner, Motoren-Werke Mannheim AG, Bonn, D

BAUER, Ernst, Redakteur, Auto Club Europa - ACE e.V. -, Stuttgart, D

BAUMANN, Günter, Dr. rer.nat., Direktor der Entwicklung, Robert Bosch GmbH, Stuttgart, D

BAUR, Ulrich, Prof. Dipl.-Ing., Gesamthochschule Duisburg, Duisburg, D

BAUR, Ing., Baur-Elektronik GmbH, Hardegsen, D

BEAVIS, Davis Andrew, Technical Liaison Engineer, Lubrizol Internation Laboratories, Hazelwood, GB

BECK, Hermann, Obering. Dipl.-Ing., Technischer Überwachungs-Verein Saarland e.V., Sulzbach, D

BECKER, A., Dr.-Ing., Papst-Motoren KG, Aachen, D

BECKHOVEN, van, Leon Christian, Ir., Ministerie van Volksgezondheid en Milieuhygiene, Leidschendam, NL

BEHRENS, Franz, Dipl.-Ing., Verband der Automobilindustrie e.V., Frankfurt, D

BELDING, John, Dr., Program Manager, National Science Foundation, Washington D.C., USA

BELLINGEN, Siegfried, Dr. rer.nat., Deutsche BP Aktiengesellschaft, Hamburg, D

BENK, Alfred, Stud. Ref., Land Niedersachsen, Hannover, D

BERG, Josef, Ing., Klöckner-Humboldt-Deutz AG, Köln, D

BERGMANN, Helmut, Dipl.-Ing., ARAL AG, Bochum, D

BERGMANN, Theo, Ing., Daimler-Benz AG, Stuttgart, D

BERNHARDT, Winfried, Dr.-Ing., Volkswagenwerk AG, Wolfsburg, D

BERTODO, Roland, Director Product Engineering, Perkins Engines Company, Peterborough, GB

BESEL, Günter, Maschinenfabrik-Augsburg-Nürnberg AG, München, D

BIERMANN, Jan Welm, Dipl.-Ing., Institut für Kraftfahrwesen, Technische Hochschule Aachen, Aachen, D

BILLMAN, Louis, Marketing Engineer, United Aircraft Corporation, Pratt & Whitney Aircraft, West Palm Beach (Florida), USA

BLOSS, Werner H., Prof. Dr.-Ing., Institut für Physikalische Elektronik der Universität Stuttgart, Stuttgart, D

BLUM, Walter, Dr.-Ing., Generalbevollmächtigter, Brown Boveri & Cie Aktiengesellschaft, Mannheim, D

BLUMENSCHEIN, Ulrich, Redakteur, Redaktion STERN, Hamburg, D

BOCHE, Heinz, Chefingenieur, Ford-Werke AG, Köln, D

BOCKELMANN, Wilfried, Dipl.-Ing., Deutsche Vergaser Gesellschaft m.b.H. & Co.KG, Neuss, D

BÖCKER, Ernst-August, Beratung, Düsseldorf, D

BÖHME, Hans-Joachim, Dr.-Ing., Prokurist, Brown Boveri & Cie Aktiengesellschaft, Mannheim, D

BOIS, Anthelme, Ing., E.C.L., Automobiles M. Berliet, Venissieux, F

BOLTEN, Gerd W.H., Direktor der Entwicklung, International Harvester Comp. m.b.H., Neuss, D

BONK, Rudolf, Ministerialrat, Bundesministerium für Verkehr, Bonn, D

BONOMOLO, Enrico, Ministero Industria, Roma, I

BORGGREFE, Dr., Regierungsrat, Bundesministerium für Wirtschaft, Bonn, D

BORN, Dipl.-Ing., Lehrstuhl für Verbrennungskraftmaschinen, Technische Hochschule Darmstadt, Darmstadt, D

BOUTHORS, Régie National des Usines Renault, Billancourt, F

BRANDSTETTER, Walter, Dr., Volkswagenwerk AG, Wolfsburg, D

BREAR, Federick, Systems Project Engineer, Perkins Engines Company, Peterborough, GB

BREITENSTEIN, Axel, Ing. (grad.), AK Chemie GmbH & Co KG, Biebesheim, D

BRESHEARS, Robert R., Mechanical Engineer, Jet Propulsion Laboratory, Pasadena (Calif.), USA

BRETTHAUER, Karlheinz, Prof., Institut für Elektrotechnik, Technische Universität Clausthal, Clausthal-Zellerfeld, D

BREVES, Otto, Dipl.-Ing., ERNO Raumfahrttechnik GmbH, Bremen, D

BROCKMANN, Heinz, Dipl.-Ing., Klöckner-Humboldt-Deutz AG, Oberursel, D

BROECKX, Willy, Senior Chemist, S.A. Texaco Belgium N.V. Ghent, Research Laboratory, Gent, B

BRÖNSTRUP, Horst, Student, Technische Hochschule Aachen, Aachen, D

BROGAN, John J., Director, Alternative Automotive Power Systems Division, Environmental Protection Agency, Ann Arbor (Mich.), USA

BROWNLEE, Michael, Professional Staffmember, U-S. Senate Committee on Commerce, Washington D.C., USA

BUCHHEIM, Rolf, Dipl.-Ing., Volkswagenwerk AG, Wolfsburg, D

BUCHNER, Helmut, Dr.-Ing., Daimler-Benz AG, Stuttgart, D

BUDDE, Hans-Jürgen, Dr. rer.pol., Dipl.-Kfm., Dipl.-Ing., Gesellschaft für elektrischen Straßenverkehr mbH, Düsseldorf, D

BULMER, Charles F., Manager, British Leyland Motor Corporation, London, GB

BUQUOY, Graf von, Rudolf, Direktor, Klöckner-Humboldt-Deutz AG, Bonn, D

BURCHARD, Klaus-Dieter, Regierungsdirektor, Bundesministerium für Wirtschaft, Bonn, D

BURGHARDT, Hans-Martin, Dipl.-Ing., Adam Opel AG, Rüsselsheim, D

BURHENNE, Interparlamentarische Arbeitsgemeinschaft, Bonn, D

BURKE, John J., Dr., Associate Director for Plans and Programs, US Army Materials Research Center, Watertown (Mass.), USA

BURTON, Rodney L., Dr., Senior Research Scientist, Steam Power Systems Inc., San Diego (Calif.), USA

BUTTGEREIT, Werner, Volkswagenwerk AG, Wolfsburg, D

CAMPION, Raymond, Dr., Research Associate, Exxon Research and Engineering Co., Linden (New Jersey), USA

CAPAUL, M., Dr., Emser Werke AG, Domat/Ems, CH

CARLQVIST, Stig G., President, United Stirling, Malmö, S

CHOPIN, Jean, Peugeot, F

CICCARONE, Angelo, Engineer, Alfa Romeo, Milano, I

COFFIELD, T.H., Dr.-Ing., Ethyl S.A., Brüssel, B

COLLIN, Karl-Heinz, Dipl.-Ing., Klöckner-Humboldt-Deutz AG, Oberursel, D

COLLIN, Lars, Prof., Institutionen för Förbränningsmotorteknik, Chalmers Tekniska Högskola, Göteborg, S

CONRAD, Oswald, Dr., Daimler-Benz AG, Stuttgart, D

CONRADS, Gerd, Student, Fachhochschule Köln, D

COPS, Michael Herbert, Electronics Engineer, Joseph Lucas Ltd., Group Research Centre, Solihull, GB

CORDES, Volker, Dipl.-Ing., AEG-Telefunken, Wedel, D

CRAMPEN, Matthias, Dipl.-Ing., Verband öffentlicher Verkehrsbetriebe, Köln, D

CREED, Alan Charles, Mechanical Engineer, CAV Ltd., London, GB

DAL BORGO, Luigi, Ing., Autoelektronik AG Chur, Locarno, CH

DARTNELL, P.L., Manager Engine Laboratory, The Associated Octel Company Ltd., Bletchley, GB

DEBLADIS, André, Responsable de la Pollution, Citroen S.A., Bureau d'Etudes Automobiles, Velizy-Villacoublay, F

DECKER, Hans-Joachim, Ing. (grad.), Battelle-Institut, Frankfurt, D

DECKER, Otto, General Manager, Mechanical Technology Incorporated, Latham (New York), USA

DEINHARDT, Hans, Ing., Prokurist, Motoren und Turbinen Union München GmbH, München, D

DEJA, Peter, Dipl.-Ing., Volkswagenwerk AG, Wolfsburg, D

DEKITSCH, Anton, Dipl.-Ing., Dornier System GmbH, Friedrichshafen, D

DEL GROSSO, Remo, Ing., ESSO Italy, Roma, I

DETHLEFSEN, Winfried, Dr., BASF AG, Ludwigshafen, D

DETTMERS, Geerd, Direktor Dipl.-Ing., Technischer Überwachungs-Verein Rheinland e.V., Koblenz, D

DICKOPP, Adolf, Ing. (grad.), RWE AG, Essen, D

DIENER, Rudolf, Ing., Autoelektronik AG Chur, Zürich, CH

DIEMAR, Wolfram, Dipl.-Ing., Institut für Elektrotechnik, Technische Universität Clausthal, Clausthal-Zellerfeld, D

DIERKS, Gunther, Volkswagenwerk AG, Wolfsburg, D

DIETRICH, Werner, Dr.-Ing., Motorenwerke Mannheim AG, Mannheim, D

DONALD, George, Civil Servant, Department of the Environment, London, GB

DREISSIGACKER, Hans-Ludwig, Ministerialrat, Bundesministerium des Innern, Bonn, D

DREYER, Pierre, Chercheur, Institut de Recherche des Transports, Bron, F

DREYHAUPT, Franz-Josef, Dr.-Ing., Ministerialdirigent, Ministerium für Arbeit, Gesundheit und Soziales des Landes Nordrhein-Westfalen, Düsseldorf, D

DÜREN, Josef, Dr.-Ing.,Technischer Überwachungs-Verein Rheinland e.V., Köln, D

DÜWEL, Ludwig, Obering., Dipl.-Ing. , Technischer Überwachungs-Verein Rheinland e.V., Köln, D

DUSAN, Gruden, Dr. techn., Dr.-Ing. h.c. F.Porsche AG, Stuttgart, D

ECKERT, Rolf, Dipl.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D

ECKSTEIN, Karl-Albert, Dipl.-Ing., Westfälische Metall Industrie KG, Lippstadt, D

EDEN, Roger Q.E., Marketing Executive, Shell International Petroleum Co. Ltd., London, GB

EGGENBERGER, Edmund, Dipl.-Volksw., Bundesverband Werkverkehr und Verlader e.V., Bonn, D

EGGER, Eugen, Dir. Dr. techn. Dipl.-Ing., Technischer Direktor, Steyr- Daimler- Puch AG, Steyr, A

EGGERT, Robert, Dipl.-Ing., International Harvester Comp. mbH, Neuss, D

EHLE, Günter, Projektbevollmächtigter für Elektrofahrzeuge, Robert Bosch GmbH, Schwiederdingen, D

EHRHARDT, Helmut, Prof. Dr. rer.nat., Präsident der Universität Trier-Kaiserslautern, Kaiserslautern, D

EIDEN, Herbert, Direktor, Technischer Überwachungs-Verein Rheinland e.V., Köln, D

EISELE, Erwin, Prof. Dr.-Ing., Daimler-Benz AG, Stuttgart, D

ELLBJÄR, Jan, AB VOLVO, Car Division, Gothenburg, S

ELLISSEN, Wolfgang, Chemie-Mineralien KG, Bremen, D

ENGELS, G., Abteilungsleiter, Ford-Werke AG, Köln, D

ESCHER, William, J.D., Technological Consultant, Escher Technology Associates, St. Johns (Mich.), USA

ESPOSITO, Vincent jr., Director of Vehicle Safety Research, Department of Transportation, Washington D.C., USA

ESSER, Jörg, Dipl.-Phys., Bundesanstalt für Straßenwesen, Köln, D

ESSERS, Ulf, Prof. Dr.-Ing., Institut für Kraftfahrwesen, Universität Stuttgart, Stuttgart, D

FARBER, Arno, Verkaufsleiter, Perkins Motoren GmbH, Kleinostheim, D

FARROW, Ivan Keith, Principal Engineer, Ford Motor Co. Ltd. England, Laindon, GB

FAUSTEN, Wilhelm, Ing. (grad.), Klöckner-Humboldt-Deutz AG., Köln, D

FAVILL, John Edward, Manager Technical Services, Norton Villiers Triumph MFG. Ltd., Wolverhampton, GB

FEDERWISCH, Jürgen, Dipl.-Ing., Stahlwerke Südwestfalen AG, Hüttental-Geisweid, D

FELGER, Gunter, Dipl.-Ing., Robert Bosch GmbH, Stuttgart, D

FEUTLINSKI, Hilmar, Fahrzeugwerkstatt Falkenried GmbH, Hamburg, D

FIEDLER, Kurt-Götz, Direktor, Kleinenbroich/Düsseldorf, D

FINKE, Wolfgang, Dr., Ministerialdirigent, Bundesministerium für Forschung und Technologie, Bonn, D

FINOS, Luigino, Alfa Romeo, Milano, I

FINSTERWALDER, Gerhard, Dipl.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D

FISCHER, Wilfried, Dr. rer.nat., Brown Boveri & Cie Aktiengesellschaft, Heidelberg, D

FLYNN, Gregory, Consulting Engineer, St. Clair Shores (Mich.), USA

FÖRSTER, Hans Joachim, Prof. Dr.-Ing., Daimler-Benz AG, Stuttgart, D

FOITZICK, Jan, Regierungsdirektor, Bayerisches Staatsministerium für Landesentwicklung und Umweltfragen, München, D

FORRESTER, R.J., Manager Engineering Division, The Associated Octel Company Ltd., Bletchley, GB

FOSTER, David B., Technischer Leiter, Perkins Engines, Kleinostheim, D

FRÄNKLE, Gerhard, Dipl.-Ing., Daimler-Benz AG, Stuttgart, D

FRANK, Max, Dipl.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D

FRANK, Werner, Direktor, techn. Diplomvolkswirt, Gesellschaft für elektrischen Straßenverkehr mbH, Düsseldorf, D

FRANKE, Gerhard, Dr.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D

FRANZKE, Dietrich, Wiss. Assistent, Institut für Verbrennungskraftmaschinen der Technischen Universität München, München, D

FRASER, Ian Anderson, Chartered Engineer, BP Trading Ltd., London, GB

FRENZEL, Dietmar, Dr., Regierungsdirektor, Bundesministerium für Forschung und Technologie, Bonn, D

FRICKE, Walter, Regierungsdirektor, Der Hessische Minister für Landwirtschaft und Umwelt, Wiesbaden, D

FRIE, Wolfgang, Dr., Siemens AG, Erlangen, D

FRIEDRICH, Rudolf, Prof. Dr.-Ing.,Lehrstuhl und Institut für Thermische Strömungsmaschinen, Universität Karlsruhe (TH), Karlsruhe, D

FRIELINGSDORF, Wolf R., Dipl.-Ing., Abteilungsleiter, Daimler-Benz AG, Stuttgart, D

FRITSCHE, Albert, Dr.-Ing., Dornier System GmbH, Friedrichshafen, D

FRUSE, Klaus, Klöckner-Humboldt-Deutz AG, Köln, D

FRYER, William Harry, Engineer, Joseph Lucas Group, Birmingham, GB

FUGMANN, Bernd, Dipl.-Ing., Allgemeiner Deutscher Automobil Club (A.D.A.C.), München, D

FUHRMANN, Ernst, Dr.-Ing., Dr.-Ing. h.c. F. Porsche AG, Stuttgart, D

FUNCKE, T.R., Dipl.-Ing., A. Ehrenreich & Cie, Düsseldorf, D

GÄFGEN, Karl, Geschäftsführer, Fritz Lange Metallwarenfabrik, Wevelinghoven, D

GANN, Andreas, Dipl.-Ing., Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt e.V., Institut für Energiewandlung und elektrische Antriebe, Stuttgart, D

GARTHE, Hellmut, Abteilungsleiter, Klöckner-Humboldt-Deutz AG, Köln, D

GASCHLER, Erich, Dipl.-Ing., Volkswagenwerk AG, Wolfsburg, D

GASPAROVIC, Nebojsa, Prof. Dr.-Ing., Technische Universität Berlin, Berlin, D

GAUSS, Fritz, Prof. Dr.-Ing., Lehrstuhl und Institut für Kraftfahrwesen, Technische Universität Hannover, Hannover, D

GAUVIN, M., Ingenieur des Mines, Ministère de l' Equipement, Arcueil, F

GAYSERT, Gerhard, Ing. (grad.), J. Eberspächer, Esslingen, D

GEFFERS, Winfried, Volkswagenwerk AG, Wolfsburg, D

GEORGI, Reinhard, Dipl.-Ing., Institut für Kraftfahrwesen, Universität Stuttgart, Stuttgart, D

GIEBEL, Gerhard, Dipl.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D

GIERA, Bernd, Dipl.-Ing., Institut für Kraftfahrwesen, Technische Hochschule Aachen, Aachen, D

GIERE, Horst-Henning, Dr., ARAL AG, Bochum, D

GIESEN, Klaus, Volkswagenwerk AG, Wolfsburg, D

GILHAUS, Alfons, Dipl.-Ing., Maschinenfabrik-Augsburg-Nürnberg AG, München, D

GLASER, Hermann, Ing., Hoechst AG, Lechenich, D

GOEDICKE, Eitel, Dr.-Ing., Hoechst AG, Knapsack, D

GOLTZ, Lothar, Dipl.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D

GONDERMANN, Horst, Dr., Direktor, ARAL AG, Bochum, D

GORUM, Alvin, Dr., Direktor, US Army Materials and Mechanics Research Center, Watertown (Mass.), USA

GRECS, Giovanni, Engineer, FIAT, Torino, I

GREEN, Fitzhugh, Associate Administrator, Environmental Protection Agency, USA

GREFEN, Klaus, Dr.-Ing., Verein Deutscher Ingenieure, Kommission Reinhaltung der Luft, Düsseldorf, D

GRIFFITH, Richard W., Prof. of Physics, Universität Bonn, Bonn, D

GRÖSCHEL, Bernhard, Dr.-Ing., ARAL AG, Bochum, D

GRÖZINGER, Hans, Dipl.-Ing., Deutsche Vergaser GmbH & Co KG, Neuss, D

GROSS, Werner, Dr.-Ing., Schäfer Einspritztechnik GmbH, München, D

GROSSMANN, Dietrich, Dr.-Ing., Deutsche Vergaser GmbH & Co KG, Neuss, D

GRUNEWALD, Dr.-Ing., Interparlamentarische Arbeitsgemeinschaft, Bonn, D

GRÜNERT, P.A., International Harvester Company mbH, Neuss, D

GRÜNLING, Herrmann, Dr.-Ing., Abteilungsleiter, Brown, Boveri & Cie Aktiengesellschaft, Mannheim, D

GUENTHER, Heinz, Dipl.-Phys., Fachbereich Physik, Universität Trier-Kaiserslautern, Kaiserslautern, D

GÜTTLER, Eugen, Brig. Gen. a.D., Dipl.-Ing., Technischer Überwachungs-Verein Rheinland e.V., Köln, D

GUIDUCCI, Rufino, Ingegnere, Ministero Interno, Roma, I

GULLON, A.C., Chief Mobile Sources Division, Abatement and Compliance Branch, Air Pollution Control Directorate, Environmental Protection Service, Ottawa, Ontario, CAN

GUTBERLET, Heiner, Dr.-Ing., Robert Bosch GmbH, Stuttgart, D

GWINNER, Dietrich, Dipl.-Ing., Hauptabteilungsleiter, Daimler-Benz AG, Stuttgart, D

GYSS, Régie National des Usines Renault, Billancourt, F

HAAS, Eckhard, Dipl.-Ing., Technischer Überwachungs-Verein Rheinland e.V., Köln, D

HABER, Friedrich, Ing. (grad.), Technischer Überwachungs-Verein Rheinland e.V., Köln, D

HÄFNER, Günther, Daimler-Benz AG, Stuttgart, D

HÄRDEN, Carl Gustaf Jan, Ingenjör, Swedish National Development Co., Stockholm, S

HÄRTEL, Günter, Ing. (grad.), Deutsche Vergaser GmbH & Co KG, Neuss, D

HAGEN, Hans, Dr.-Ing., Maschinenfabrik-Augsburg-Nürnberg AG, München, D

HAGEN-FREUSBERG, Alexander, Vorstandsvorsitzender, Gottfried Hagen AG, Köln, D

HAGEMEISTER, Klaus, Dipl.-Ing., Abteilungsleiter, Motoren und Turbinen Union München GmbH, München, D

HAILER, Karl-Ernst, Prof. Dipl.-Ing., Automobiltechnische Zeitschrift, Ruit a.F., D

HALDER, Heinz, Baudirektor, Stadtwerke-Verkehrsbetriebe München, München, D

HALLARE, Bengt G., Marketing Manager, United Stirling, Malmö, S

HAMILTON, William, Director, Urban Transportation Programs, General Research Corporation, Goleta (Calif.), USA

HARMON, Robert A., Consultant, Mechanical Technology Inc., Latham, N.Y., USA

HARRIS, Tex, Environmental Protection Agency, USA

HARRISON, G.F., Technical Manager, The Associated Octel Comp. Ltd., London, GB

HARTGES, Hans-Joachim, Dipl.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D

HARTIG, Fritz, Dipl.-Ing., Dr.-Ing. h.c. F. Porsche AG, Stuttgart, D

HARTKOPF, Günter, Dr., Staatssekretär, Bundesministerium des Innern, Bonn, D

HARTMANN, Albrecht, Dr., Abteilungsleiter, Audi NSU Auto Union AG, Neckarsulm, D

HARTMANN, Dietrich, Dr., Vizepräsident, Umweltbundesamt Berlin, D

HARVEY, Dennis, International Nickel Ltd., London, GB

HASELHORST, Manfred, Dr. rer.nat., VEBA-Chemie AG, Gahlen, D

HASENZAHL, Rudolf, Dipl.-Ing., Direktor, Daimler-Benz AG, Stuttgart, D

HATTINGEN, Ulrich, Dr.-Ing., Naturwissenschaftlich - Technische Fakultät der Universität Trier-Kaiserslautern, Fachbereich Maschinenwesen/Elektrotechnik, Kaiserslautern, D

HAUSCHILDT, Henry, Obering., Deutsche BP AG, Institut für Forschung und Entwicklung, Hamburg, D

HASSEL, Dieter, Dipl.-Ing., Technischer Überwachungs-Verein Rheinland e.V., Köln, D

HEDDE, Michel, Techn. Manager, Octel S.A., Paris, F

HEIDEMEYER, Paulus, Dipl.-Ing., Volkswagenwerk AG, Wolfsburg, D

HEILBUT, Hellfried, Marketing Manager, Automotive Products Division, Universal Oil Products Company, Hamburg, D

HEITLAND, Herbert, Prof. Dr.-Ing., Volkswagenwerk AG, Wolfsburg, D

HELLERMANN, Karlheinz, Ing., Bundesministerium für Verteidigung, Bonn, D

HELLING, Jürgen, Prof. Dr.-Ing., Institut für Kraftfahrwesen, Technische Hochschule Aachen, Aachen, D

HELLMICH, Klaus, W., Ing. (grad.), Kfz-Sachverständiger, Deutscher Kraftfahrzeug-Überwachungsverein, Bochum, D

HELM, Klaus, ARAL AG, Bochum, D

HENKEL, H.-J., Dr., Siemens AG, Erlangen, D

HENSEL, J., Dr., Degussa Wolfgang, Hanau, D

HENSSLER, Hans-Dieter, Dr.-Ing., Kühnle, Kopp & Kausch, Frankenthal, D

HENSSLER, Herbert, Dipl.-Ing., Verwaltungsrat, Kommission der Europäischen Gemeinschaften, Brüssel, B

HENTSCHEL, Heinrich, Prof. Dr.-Ing., Fachhochschule Rheinland-Pfalz, Fachrichtung Verbrennungskolbenmaschinen, Kaiserslautern, D

HERR, E.A., Düsseldorf, D

HERMANS, Mathias Leonardus, Ir., Philips Research Laboratories, Eindhoven, NL

HERSCHMANN, Otto, Dr.-Ing., Technischer Vorstand Klöckner-Humboldt-Deutz AG, Köln, D

HESSE, Ernst Oswald, Konsul, E.O. Hesse, Erkrath, D

HETZEL, Heinrich, Dipl.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D

HEYSER, Alfred, Prof. Dr.-Ing., Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt e.V., Institut für Angewandte Gasdynamik, Porz-Wahn, D

HIERETH, H., Dipl.-Ing., Daimler-Benz AG, Stuttgart, D

HILGERFELD, Horst-Walter, Dipl.-Ing., Dipl.-Wirtsch. Ing., Wirtschaftsberatung AG, Düsseldorf, D

HINGST, Martin, Rheydt, D

HINZ, Dieter, Laboringenieur, Fachhochschule Köln, Köln, D

HIRSCHBERGER, Hans-G., Direktor, Technischer Überwachungs-Verein Rheinland e.V., Köln, D

HOAGLAND, Lawrence C., Dr.-Ing., Vicepresident - Director of Research, Scientific Energy Corporation, Watertown (Mass.), USA

HOCKEL, Knut, Dipl.-Ing., Bayerische Motoren Werke AG, München, D

HÖRDEGEN, Hans, Dipl.-Ing., Technischer Überwachungs-Verein Bayern e.V., München, D

HOFBAUER, Peter, Dipl.-Ing. Volkswagenwerk AG, Wolfsburg, D

HOFERER, Hans J., Dipl.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D

HOHENBERG, Dr.-Ing., Hohengehren, D

HOLTHAUSEN, Dieter, Dipl.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D

HOLZAPFEL, Immanuel, Abteilungsleiter, Daimler-Benz AG, Stuttgart, D

HOPE, Jack I., General Manager, General Electric Co., Cincinnati (Ohio), USA

HOPMANN, Helmut, Dipl.-Ing., Messerschmitt-Bölkow-Blohm GmbH, München, D

HORCH, Eberhard-Josef, Dipl.-Ing., Universität Stuttgart, Stuttgart, D

HORN, Lutz, Dr., Gottfried Hagen AG, Köln, D

HORSTMANN, B., International Harvester Company mbH, Neuss, D

HUBER, E.W., Prof. Dr.-Ing., Institut für Verbrennungsmotoren und Arbeitsmaschinen der Universität Stuttgart, Stuttgart, D

HUBNER, George, Director of Research, Chrysler Corp., Highland Park (Mich.), USA

HUCHO, Wolf-H., Dr.-Ing., Forschungsleiter, Volkswagenwerk AG, Wolfsburg, D

HUE, Baur-Elektronik GmbH, Hardegsen, D

HÜBER, Gerd, Dipl.-Ing., Obering., Vereinigung der Technischen Überwachungs-Vereine e.V., Essen, D

HÜHN, Walter, Dr.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D

HUGOSSON, Sven, Chief Engineer, Swedish National Development Co., Stockholm, S

HUNDT, Eberhard, Dipl.-Ing., Wankel GmbH, Stuttgart, D

HURN, R.W., Research Supervisor, Fuels Combustion Research Group, Bartlesville Energy Research Center, Bartlesville (OK), USA

HURTER, Donald A., Senior Consultant, Arthur D. Little Inc., Cambridge, (Mass.), USA

HUSSMANN, Albrecht W., Prof. Dr.-Ing., Lehrstuhl und Institut für Verbrennungskraftmaschinen und Kraftfahrzeuge, Technische Universität München, München, D

HUSTED, Robert A., Staff Engineer, U.S. Department of Transportation, Washington, D.C., USA

IKEME, Kiyoshi, Planning Manager, Honda Motor Co. Ltd., Tokyo, J

INOUE, Kazuo, Düsseldorf, D

INUI, Saburo, Toyota Motor Co. Ltd., Brüssel, B

IWAI, Nobuo, Research Engineer, Japan Automobile Research Institute Inc.,
Ibaraki, J

JACOBY, Ewald, Ing. (grad.), Kühnle, Kopp & Kausch, Frankenthal, D

JAEGER, Karl, Ing. (grad.), Dornier System GmbH, Friedrichshafen, D

JÄSCHKE, Alfons, Ing. (grad.), Klöckner-Humboldt-Deutz AG, Köln, D

JAHNKE, Horst, Dr. rer.nat., Robert Bosch GmbH, Stuttgart, D

JANSSEN, Manfred, Mannesmannröhren-Werke AG, Düsseldorf, D

JEZIC, Vladimir, Dipl.-Ing., Darmstadt, D

JOHN, Veit, Ing. (grad.), Hoechst AG, Frankfurt, D

JONES, Key, Dr., Director, NATO-CCMS Air Pollution Pilot-Study,
Environmental Protection Agency, Ann Arbor (Mich.), USA

JONETZKI, Norbert, Kfz.-Ing. (grad.), L. Kostal, Lüdenscheid, D

JORISSEN, H. Dieter, Dipl.-Ing., Redaktion VDI-Nachrichten, Düsseldorf, D

JOSHI, Suray, Versuchsleiter, Klöckner-Humboldt-Deutz AG, Köln, D

JOST, Peter, Dr.-Ing., Technischer Überwachungs-Verein Rheinland e.V.,
Köln, D

JUNG, Dieter, Dipl.-Ing., Brown, Boveri & Cie Aktiengesellschaft,
Mannheim, D

JUST, Thomas, Dr., Direktor, Deutsche Forschungs- und Versuchsanstalt
für Luft- und Raumfahrt e.V., Institut für Reaktionskinetik,
Stuttgart, D

KAISER, Wilfried, Dr.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D

KANT, Fred, Dr.-Ing., Exxon Research and Engineering Company, Linden
(New Jersey), USA

KATZ, Robert, Dr., Chief, Ceramics Research Division, US Army
Materials and Mechanics Research Center, Watertown (Mass.), USA

KAYSER, Albrecht, Dipl.-Ing., Deutsche Forschungs- und Versuchsanstalt
für Luft- und Raumfahrt e.V. - Luftstrahlantriebe, Porz-Wahn, D

KEEN, Peter, Staff Engineer, AB VOLVO, Car Division, Gothenburg, S

KEILPFLUG, Werner, Dipl.-Ing., Bonn, D

KERGEL, Ernst-Christian, Wirtsch.-Ing., Bayer Rickmann GmbH, Köln, D

KEYLWERT, Johann, Dir. Dipl.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D

KHADEM, Fereidoun, Dipl.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D

KIEFER, Edwin S., Exekutiv-Ing., Adam Opel AG, Rüsselsheim, D

KILLMANN, Irolt, Dr.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D

KIMPE, Joseph G., Mechanical Engineer, S.A. Texaco Belgium N.V.
Ghent-Research Laboratory, Gent, B

KINDLER, Friedrich, Dipl.-Ing., Abteilungsleiter, Klöckner-Humboldt-Deutz
AG, Köln, D

KINOSHITA, Keijiro, Principal Research Engineer, Nissan Motor Comp.
Ltd., Yokosuka, J

KIRCHHOFF, William Hayes, Deputy Manager, National Bureau of Standards,
U.S. Department of Commerce,Washington D.C., USA

KLAMANN, Dieter, Prof. Dr., ESSO AG, Forschungszentrum, Hamburg, D

KLEINSCHMIDT, Walter, Dr.-Ing., Lehrstuhl für Angewandte Thermodynamik,
Technische Hochschule Aachen, Aachen, D

KLINGENBERG, Horst, Dipl.-Phys.,Dr. rer.nat., Volkswagenwerk AG,
Wolfsburg, D

KLÖCKER, Karl-Josef, Dipl.-Ing., Lehrstuhl für Angewandte Thermodynamik,
Technische Hochschule Aachen, Aachen, D

KNÖÖS, Stellan, Dr., Consultant, Malibu (Calif.), USA

KNCERNSCHILD, Eugen, Prof., Deutsche Forschungs- und Versuchsanstalt
für Luft- und Raumfahrt e.V., Stuttgart, D

KNOPPER, M.J.F., BK Gas, Barnevald, NL

KNUST, Dieter, Redakteur, Kölnische Rundschau, Motoren-Redaktion, Köln,D

KOCH, Gerhard, Dr., Kali-Chemie AG, Hannover, D

KOCH, Helmut, Ing., Deutsche Forschungs- und Versuchsanstalt für Luft-
und Raumfahrt e.V., Faßberg, D

KOCH, Wolf H., Dr.-Ing., Institut für Elektrische Maschinen, Technische
Universität Hannover, Hannover, D

KÖHLER, Gerhard, Maj., Dipl.-Ing., Fachhochschule des Heeres 1,
Darmstadt, D

KÖHLER, Wolfgang, Dr.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D

KOENHORN, Dieter, ARAL AG, Bochum, D

KÖNIG, Wolfgang, Oberregierungsbaurat, Dipl.-Ing., Bundesamt für Wehrtechnik und Beschaffung, Koblenz, D

KÖPCKE, Günter, Ing., Deutsche Texaco AG, Hamburg, D

KÖPKE, Norbert, European Honda Motor Trading GmbH, Offenbach, D

KOLLMANN, Karl, Dr.-Ing., Warmbronn, D

KORDES, August, Dir. Dipl.-Ing., Technischer Überwachungs-Verein Rheinland e.V., Düsseldorf, D

KORKMAZ, Feridun, Wissenschaftl. Assistent, Institut für Landverkehrsmittel, Technische Universität Berlin, Berlin, D

KOSTKA, Hana, Siemens AG, Erlangen, D

KOTAUSCHEK, Walter, Ing., Klöckner-Humboldt-Deutz AG, Köln, D

KRAATZ, Detlef, Obering. Dipl.-Ing., Stahlwerke Südwestfalen, Hüttental-Geisweid, D

KRAEGE, Hans-Jürgen, Dr., Regierungsdirektor, Bundesministerium für Forschung und Technologie, Bonn, D

KRAFT, Hans-Joachim, Bereichsleiter, Bayerische Motoren Werke AG, München, D

KRAMER, Klaus, Dipl.-Ing., Technische Hochschule Aachen, Aachen, D

KRANZ, P., International Harvester Company mbH, Neuss, D

KRAULAND, Prof. Dipl.-Ing., Fachhochschule Köln, Fachbereich Fahrzeugtechnik, Köln, D

KRAUSE, Peter, Dipl.-Ing., Heinrich Gillet KG, Edenkoben, D

KRELL, Karl, Prof. Dr.-Ing., Bundesanstalt für Straßenwesen, Köln, D

KRIEG, Helmut, Leiter Kfz.-und Verkehrsgesetzgebung, Ford-Werke AG, Köln, D

KRONOGARD, Sven-Olof, Managing Director, United Turbine AB & COKB, Malmö, S

KRÜGER, Hans, Robert Bosch GmbH, Köln, D

KRUGGEL, Otto, Dr.-Ing., Motoren- und Turbinen-Union Friedrichshafen GmbH, Friedrichshafen, D

KÜHN, Martin, Prof. a.D., Düsseldorf, D

KÜHN, Reiner, Dr.-Ing., Unionkraftstoff AG, Wesseling, D

KÜPPER, Heinz, Ing. (grad.), Klöckner-Humboldt-Deutz AG, Köln, D

KÜSTER, Berthold, Hauptverwaltungsrat, Generalsekretariat des Europäischen Parlaments, Ausschuß für Volksgesundheit und Umweltfragen, Luxemburg, L

KUHLA, Eckhard, Bahnrat, Deutsche Eisenbahn-Consulting GmbH, Frankfurt, D

KUHLMANN, Albert, Prof. Dr.-Ing., Geschäftsführender Direktor, Technischer Überwachungs-Verein Rheinland e.V., Köln, D

KUHLMANN, Peter, Dr.-Ing., Maschinenfabrik-Augsburg-Nürnberg AG, Augsburg, D

KUIPERBAK, Johan George, Ir., Director of the State Office of Road Traffic, Ministry of Transport and Public Works Den Haag, NL

KULLBERG, Gösta, Head of the Dep. of Technology of Ground Vehicles, The Royal Institute of Technology, Stockholm, S

KUNBERGER, Klaus, Editor, Diesel and Gas Turbine Progress, Leonberg, D

KUND, A., Senior Ing., Ford-Werke AG, Bonn, D

KURZ, Heinz, Dipl.-Ing., Deutsche Eisenbahn-Consulting GmbH, Frankfurt, D

KUSHIYAMA, Tadashi, Doctor of Mechanical Engineering, Nagasaki Technical Institute, Mitsubishi Heavy Industries Ltd., Nagasaki, J

KUSSMANN, L.W., Adam Opel AG, Rüsselsheim, D

KUTZNER, Klaus, Dr., Senator Gesundheit und Umweltschutz, Berlin, D

LABUS, Herwig, Dr. rer.nat., Kernforschungsanlage Jülich GmbH, Jülich, D

LAHMANN, Erdwin, Direktor und Prof. Dr., Institut für Wasser-, Boden- und Lufthygiene des Bundesgesundheitsamtes, Berlin, D

LAMURE, M., Centre de Recherche de l'Institut de Recherche des Transports, F

LANGE, Karlheinz, Dr.-Ing., Dr.-Ing. h.c. F. Porsche AG, Weissach, D

LAPEDES, Donald E., Program Manager, The Aerospace Corporation, El Segundo (Calif.), USA

LATSCH, Reinhard, Dr.-Ing., Robert Bosch GmbH, Stuttgart, D

LAUMANN, Hans-Jürgen, Ing. (grad.), Wintershall AG, Kassel, D

LEDWINKA, Erich, Dipl.-Ing., Direktor, Steyr-Daimler-Puch AG, Graz-Thondorf, A

LEE, Wenpo, Dr.-Ing., Volkswagenwerk AG, Wolfsburg, D

LEIPFINGER, Hugo, Dr. rer.nat., Linde AG, Höllriegelskreuth, D

LEISEN, Peter, Dipl.-Ing., Technischer Überwachungs-Verein Rheinland e.V., Köln, D

LENOE, Edward, Dr. Chief, Mechanics Materials Division, US Army Materials and Mechanics Research Center, Watertown (Mass.), USA

LEPPERHOFF, Gerhard, Dipl. Ing., Lehrstuhl für Angewandte Thermodynamik, Technische Hochschule Aachen, Aachen, D

LETTNER, Kurt, Dr. Dipl.-Ing., Steyr-Daimler-Puch AG, Steyr, A

LEWIS, Leon David, Project Engineer, Garrett Corporation of California, Torrance (Calif.), USA

LINCKE, Dr., Leitung der Forschung, Volkswagenwerk AG., Wolfsburg, D

LINDEMANN, Gerhard, Klöckner-Humboldt-Deutz AG, Köln, D

LINDER, Ernst, Dipl.-Ing., Robert Bosch GmbH, Stuttgart, D

LINES, David John, Chartered Engineer, Lucas Group Research Centre, Solihull, GB

LINKE, Harald, Presseleiter, Brüggemann & Co GmbH, Düsseldorf, D

LJUNGSTRÖM, Olle, Dr., Swedish Board for Technical Development, Stockholm, S

LOEFFLER, Lawrence E., Marketing Manager, NV. Philips, Briarcliff Manor (New York), USA

LÖHNER, Kurt, Prof. Dr.-Ing. (em.), Institut für Verbrennungskraftmaschinen, Technische Universität Braunschweig, Braunschweig, D

LOHR, F., Adam Opel AG, Rüsselsheim, D

LOSENKY, Werner, Ing., Zentralverband des Kfz.-Handwerks, Bonn, D

LUDWIG, John H., Dr., Consultant, Environmental Protection Agency, USA

LÜTKES, Hermann, Dr., Ministerialrat, Bundesministerium für Verkehr, Bonn, D

LUX, G., Adam Opel AG, Rüsselsheim, D

LYNCH, Brian, Dr.-Ing., N.V. Philips Gloeilampenfabrieken, Eindhoven, NL

MAASS, Karl, Dipl.-Ing., AEG-Telefunken, Wedel, D

MACHER, Karl, Dipl.-Ing., Deutsche Vergaser GmbH & Co KG, Neuss, D

MAHN, Gerhard, Obering. Dipl.-Ing., Farbwerke Hoechst AG, Frankfurt, D

MAIER, Siegfried, Dipl.-Ing., Kühnle, Kopp & Kausch, Frankenthal, D

MALMRUP, Lars, Assistant Managing Director, United Turbine AB & CO KB, Malmö, S

MALTZ, Ing., Baur-Elektronik GmbH, Hardegsen, D

MALY, Rudolf, Dipl.-Ing., Institut für Physikalische Elektronik der Universität Stuttgart, Stuttgart, D

MANGER, Hansjörg, Dr., Robert Bosch GmbH, Stuttgart, D

MARTIN, Karl-Ulrich, Ing. (grad.), Umweltbundesamt, Berlin, D

MASINA, Ruggero, Ing., Autoelektronik AG Chur, Zürich, CH

MATTHÖFER, Hans, Bundesminister für Forschung und Technologie, Bonn, D

MAUCH, Harald, Dr.-Ing., Robert Bosch GmbH, Stuttgart, D

MAY, Hans, Prof. Dr.-Ing., Naturwissenschaftlich - Technische Fakultät der Universität Trier-Kaiserslautern, Fachbereich Maschinenwesen/Elektrotechnik, Kaiserslautern, D

MAY, Wolfgang, Dipl.-Ing., Technischer Überwachungs-Verein Rheinland e.V., Köln, D

MAYER, Andreas, Dipl.-Ing., AG Brown, Boveri & Cie, Baden, CH

MC ADOW, Theodore, Mechanic, Chrysler Corporation, Chatham (Mich.), USA

MC LAUGHLIN, David, B. Sc., Advanced Materials Engineering Ltd., Gateshead, GB

MC LEAN, Arthur F., Manager, Turbine Development Department, Ford Motor Company, Dearborn (Mich.), USA

MEDENUS, Bernhard, Dipl.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D

MEIJER, Roelof Jan, Dr.Ir., Director of Research, N.V. Philips Gloeilampenfabrieken, Eindhoven, NL

MEISCHNER, Peter, Dr. rer.nat., Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt e.V., Programmvorbereitung, Porz-Wahn, D

MELSHEIMER, Jürgen, Ing., Sandvikstahl GmbH, Düsseldorf, D

MELTZER, J., Dr., Aerospace Corp., Los Angeles, USA

MELZER, Dipl.-Ing., Lehrstuhl für Verbrennungskraftmaschinen, Technische Hochschule Darmstadt, Darmstadt, D

MENKE-GLÜCKERT, P., Ministerialdirigent, Bundesministerium des Innern, Bonn, D

MENRAD, Holger, Dipl.-Ing., Volkswagenwerk AG, Wolfsburg, D

MENZL, Karl Heinz, Dipl.-Ing., Volkswagenwerk AG, Wolfsburg, D

MERKLE, Roland, Dipl.-Ing., Abteilungsleiter, Daimler-Benz AG, Stuttgart, D

MERTINS, Erich, Ing. (grad.), Technischer Überwachungs-Verein Rheinland e.V., Köln, D

MERTZIG, Walter, Journalist, Technischer Überwachungs-Verein Rheinland e.V., Köln, D

MESTWERDT, Rolf, Phys.-Ing., Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt e.V., Institut für Chem. Raketenantriebe, Faßberg, D

MEURER, J. Siegfried, Prof. Dr.-Ing. E.h. Dr.-Ing., Vorstandsmitglied, Maschinenfabrik-Augsburg-Nürnberg AG, Augsburg, D

MEYER, Wolfgang, Dr.-Ing., Verkehrswissenschaftliches Institut, Technische Hochschule Aachen, Aachen, D

MICHEL, Alfred, Dr., Siemens AG, Erlangen, D

MIEBACH, Rolf, Klöckner-Humboldt-Deutz AG, Köln, D

MITCHELL, John E., Director of Research, Caterpillar Tractor Co. Ltd., London, GB

MÖLDNER, Oberamtsrat,Bundesministerium für Wirtschaft, Bonn, D

MÖNNER, Wolfgang, Dr.-Ing., Technischer Überwachungs-Verein Rheinland e.V., Köln, D

MOLLENHAUER, Klaus, Prof. Dr.-Ing., Technische Universität Berlin, Berlin, D

MORSE, Richard S., Chairman, Scientific Energy Systems Corp. (SES), Watertown (Mass.), USA

MOYER, David F., Director, Systems Research Laboratory, Ford Motor Company, Dearborn (Mich.), USA

MÜHLBERG, Erhard, Prof. Dr.-Ing., Institut für Verbrennungskraftmaschinen, Technische Hochschule Darmstadt, Darmstadt, D

MÜLLER, Hans-Georg, Dr.-Ing., Gesellschaft für elektrischen Straßenverkehr mbH, Düsseldorf, D

MÜLLER, Herbert, Wiss. Rat und Prof. Dr.-Ing., Institut für Verbrennungskraftmaschinen, Technische Universität Braunschweig, Braunschweig, D

MÜLLER, Jochen, Klöckner-Humboldt-Deutz AG, Köln, D

MÜLLER, Klaus, Dipl.-Ing., ESSO AG Forschungszentrum, Hamburg, D

MÜLLER-BERNER, Alfred, Dr.-Ing., Daimler-Benz AG, Stuttgart, D

MUHR, Heinz, Ing. (grad.), A. Ehrenreich & Cie, Düsseldorf, D

MURRMANN, Wolfgang, Verkaufsleiter, European Honda Motor Trading GmbH, Offenbach, D

MUSCHACK, Werner, Dipl.-Chem., Verein Deutscher Ingenieure, Kommission Reinhaltung der Luft, Düsseldorf, D

MYERS, Nancy S., International Activities Coordinator, Office of Air and Waste Management, Environmental Protection Agency, USA

NADIM, François, Ingénieur, Le Moteur Moderne, Boulogne, F

NAGEL, Axel, Dipl.-Ing., Daimler-Benz AG, Stuttgart, D

NAGEL, Siegfried, Redakteur, Handelsblatt, Die technische Linie, Düsseldorf, D

NAITO, M., Yamaha Motor N.V., Amstelveen, NL

NEBER, Richard, Dr.-Ing., Mahle GmbH, Stuttgart, D

NEUBAUR, Hans Peter, Dipl.-Ing., Dornier System GmbH, Friedrichshafen, D

NEUMANN, Reiner, Dipl.-Phys., Walker Manufact., Viernheim, D

NIEMEYER, Arno, Kfz.-Meister, Calor-Gas GmbH, Wuppertal, D

NIERHAUVE, Bernd, Ing. (grad.), ARAL AG, Bochum, D

NOLL, Paul H., Verkaufsleiter, Engelhard Kali-Chemie AutoCat GmbH, Hannover, D

NORMAN, Thomas A., Manager, Transportation Branch, United States Postal Service, Rockville (Maryland), USA

NOTH, Dipl.-Ing., Deutsche Forschungsgemeinschaft, Ref. Ingenieurwissenschaften 1, Bonn, D

OBLÄNDER, K., Dipl.-Ing., Daimler-Benz AG, Stuttgart, D

OEHLER, Franz, Oberleutnant, Luftwaffenamt, General Luftwaffenrüstung, Porz-Wahn, D

OEHMS, Klaus-Joachim, Dipl.-Ing., RWE AG, Essen, D

OELERT, Henning, Prof. Dr. rer.nat., Institut für Technische Chemie, Technische Universität Hannover, Hannover, D

ÖRTEGREN, Lars, Managing Director, HB Development AB, Stockholm, S

OHRT, Udo, Dr.-Ing., Technischer Überwachungs-Verein Rheinland e.V., Köln, D

OPPORTUNO, Vincenzo, Ministero Transporti, Roma, I

OTTO, Volker, Dipl.-Ing., Garrett München, München, D

OZDAS, Nimet, Prof., Assistant Sect.-General for Scientific and Environmental Affairs, NATO

PALMER, Robert John, Civil Servant, Department of the Environment, London, GB

PALMER, Roy Michael, Chartered Engineer, Ricardo & Co. Engineers Ltd., Shoreham-by-Sea, GB

PAPST, Hans Dieter, Dipl.-Ing., Papst-Motoren KG, St. Georgen, D

PAPST, Hermann, Geschäftsführer, Papst-Motoren KG, St. Georgen, D

PARKER, Andrew J., Jr., Vice President, Richard P. Mueller and Associates, Inc., Baltimore (Maryland), USA

PARR, Oswald, Dr.-Ing., Filterwerk Mann & Hummel GmbH, Ludwigsburg, D

PATEL, Parimal, Program Manager, Thermo Electron Corporation, Waltham (Mass.), USA

PAUL, Bernt, Dr., Siemens AG, Erlangen, D

PAUSE, Werder, Dr.-Ing., Bayerische Motorenwerke AG, München, D

PERSSON, Sven G., Project Engineer, Saab- Scania AB, Linköping, S

PERTEK, Peter, Daimler-Benz AG, Stuttgart, D

PETERMANN, Hubertus, Leiter der Konstruktion, Eaton GmbH, Velbert, D

PFLEGHAAR, Anton, Dipl.-Ing., Motoren Werke Mannheim AG, Mannheim, D

PICKERT, Helmut, Dipl.-Ing., Kühnle, Kopp & Kausch, Frankenthal, D

PIPPERT, Prof. Dr.-Ing., Fachhochschule Köln, Fachbereich Fahrzeugtechnik, Köln, D

PISCHINGER, Franz, Prof. Dr. techn., Lehrstuhl für Angewandte Thermodynamik, Technische Hochschule Aachen, Aachen, D

PISCHINGER, Georg, Dr. Dipl.-Ing., Audi NSU Auto Union AG, Ingolstadt, D

PITSCH, G., Ford Motor Company, Dearborn (Mich.), USA

PLASSMANN, Eberhard, Dr.-Ing., Technischer Überwachungs-Verein Rheinland e.V., Köln, D

PLUST, Heinz, Dr.-Ing. Dipl.-Ing. Dipl.-Chem, Direktor, Deutsche Automobilgesellschaft mbH, Esslingen-Mettingen, D

PÖHLS, Herbert, Dipl.-Ing., Technische Universität Berlin, Fachbereich 12, Berlin, D

POHLE, Jürgen, Dipl.-Ing., Volkswagenwerk AG, Wolfsburg, D

POLACH, Wilhelm, Dipl.-Ing., Dozent, Technische Hochschule Darmstadt, Darmstadt, D

POLZ, H., Dipl.-Ing., Daimler-Benz AG, Stuttgart, D

PRAHL, Jürgen, Ing., ERN Motorenteile KG, Düsseldorf, D

PRESCHER, Karl Heinz, Dr.-Ing., Institut für Motorenbau Prof. Huber e.V., München, D

PRESS, Rudi, Kfz.-Meister, Farbwerke Hoechst AG, Frankfurt, D

PROFF, Régie National des Usines Renault, Billancourt, F

PROPFE, Günter, Dipl.-Ing., Deutsche BP Aktiengesellschaft, Hamburg, D

PÜTZ, Karl, Obering., Klöckner-Humboldt-Deutz AG, Köln, D

QUILICI, M., Conseiller Technique pour les Affairs Automobiles, Ministère de l'Industrie, du Commerce et de l'Artisanat, Paris, F

RADERMACHER, Karlheinz, Dr.-Ing., Stellvertretendes Vorstandsmitglied, Bayerische Motoren Werke AG, München, D

RAGONE, David V., Prof.-Engineering, The University of Michigan, Dean of Engineering, Ann Arbor (Mich.), USA

RAMSDEN, Albert William, Principal Research Scientist, ESSO Research Center, Abingdon, GB

RAU, Werner, Ing. (grad.), Brown, Boveri & Cie Aktiengesellschaft, Mannheim, D

RAUSSENDORF, Curt, Dr. agr., Obering., Verein Deutscher Ingenieure, Fachgruppe Fahrzeugtechnik, Düsseldorf, D

RAUSSENDORF, Werner, Ing. (grad.), Verein Deutscher Ingenieure, Fachgruppe Fahrzeugtechnik, Düsseldorf, D

REBER, Harald, Dr.-Ing., Robert Bosch GmbH, Stuttgart, D

REBHING, Peter, Kühnle, Kopp & Kausch, Frankenthal, D

RECHBERG, Reinhard, Klöckner-Humboldt-Deutz AG, Köln, D

REIMANN, Jochen, Dipl.-Ing., Institut für Kraftfahrwesen, Technische Hochschule Aachen, Aachen, D

REINHARDT, Gerd R., Dipl.-Ing., ARAL AG, Bochum, D

REINIGER, Karl-Hellmuth, Dipl.-Ing., Battelle-Institut e.V., Frankfurt, D

REMMETS, Theodor, Dipl.-Ing., Union Kraftstoff AG, Wesseling, D

RENNER, Roy A., Consulting Engineer, Technical Manager, California Clean Car Project, California State Assembly, Livermore (Calif.), USA

REULEAUX, Chr., Dr., Engelhard Kali-Chemie, AutoCat GmbH, Hannover, D

REULEIN, Hermann, Dr.-Ing., Deutsche Vergaser GmbH & Co KG, Neuss, D

REUSS, Hans-Jürgen, Obering., Fachjournalist, Lohmar, D

RICHARDSON, Robert W., Manager, Technological Planning, Eaton Corporation, Southfield (Mich.), USA

RICHTER, Immo, Dipl.-Ing., Motoren- und Turbinen-Union Friedrichshafen GmbH, Friedrichshafen, D

RIED, Willi, Pensionär, Daimler-Benz AG, Stuttgart, D

RIORDAN, Barrett, Senior Staff Member, U.S. Consul on Environmental Quality, USA

RIXMANN, Werner, Prof. Dr.-Ing., Redaktion Automobiltechnische Zeitschrift, Esslingen, D

RODENBUSCH, Heinz, Dr., Mobil Oil AG, Wedel, D

RÖHRLE, Manfred, Dr.-Ing., Mahle GmbH, Stuttgart, D

ROERTGEN, Horst, Dr.-Ing., Lehrstuhl für Technische Thermodynamik, Technische Hochschule Aachen, Aachen, D

ROGGENDORF, Martin, Obering. Dipl.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D

ROHDE, Siegfried, Dipl.-Ing., Institut für Verbrennungskraftmaschinen, Technische Universität Braunschweig, Braunschweig, D

ROHR, Franz-Josef, Dr. rer.nat., Brown, Boveri & Cie Aktiengesellschaft, Heidelberg, D

ROHS, Ulrich, Dipl.-Ing., Institut für Kraftfahrwesen, Technische Hochschule Aachen, Aachen, D

ROLF, Hermann, Gewerbedirektor, Technisches Überwachungsamt, Frankfurt, D

ROSSENBECK, Martin, Dr.-Ing., Direktor, ARAL AG, Bochum, D

ROWOLD, Karl-Joachim, Ing. (grad.), Battelle-Institut e.V., Frankfurt, D

RÜSBERG, Ernst, Vorstandsmitglied, Kali-Chemie AG, Hannover, D

SÄUFFERER, Helmut, Dr. rer.nat., Daimler-Benz AG, Stuttgart, D

SAGGAU, Boye, Dr.-Ing., Institut für Physikalische Elektronik der Universität Stuttgart, Stuttgart, D

SALAMON, Klaus, Dr.-Ing., VARTA Batterie AG, Kelkheim, D

SANDERS, Cameron, CCMS Officer, United States Delegation to NATO

SATO, Shiro, Japan Automobil Research Institution, Tokyo, J

SAUERTEIG, Enrique, Dipl.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D

SAVONUZI, Giovanni, Ing., Direttore, Direzione Ricerca Tecnoligica, FIAT, Torino, I

SAWYER, Robert F., Prof., University of California, Department of Mechanical Engineering, Berkeley (Calif.), USA

SEBESTYN, Thomas, Manager, Gas Turbine Section, Alternative Automotive Power Systems Division, Environmental Protection Agency, USA

SEEGER, Arnold, Dipl.-Ing., Kernforschungsanstalt Jülich GmbH, Jülich, D

SEIDEL, Günter H., ARAL AG, Bochum, D

SEIFERT, Günter, Dipl.-Ing., BOR., Bundesministerium für Verkehr, Bonn, D

SEIFERT, Hans, Prof. Dr.-Ing., Ruhr-Universität, Bochum, D

SEIFERT, Karl-Heinz, Dipl.-Ing., ARAL AG, Bochum, D

SELLSCHOPP, Friedhart, Dr., Oberregierungsbaurat, Bundesministerium der Verteidigung, Bonn, D

SEUFER, Theo, Dipl.-Ing., Audi NSU Auto Union AG, Neckarsulm, D

SICKEN, Heinz, Technischer Überwachungs-Verein Rheinland e.V., Köln, D

SIEBS, Enno, Dipl.-Ing., ESSO AG Forschungszentrum, Hamburg, D

SIEGEL, Jeffrey R., Science Officer, Amerikanische Botschaft, Bonn-Bad Godesberg, D

SIENČNIK, L., Dipl.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D

SIERING, Rolf, Dipl.-Ing., ESSO AG Forschungszentrum, Hamburg, D

SIEWEK, Klaus D., Ing. (grad.), AK-Chemie GmbH & Co KG, Biebesheim, D

SIEWERT, Ing. (grad.), Fachhochschule Köln, Fachbereich Fahrzeugtechnik, Köln, D

SIMON, Michael, Dipl.-Ing., Maschinenfabrik-Augsburg-Nürnberg AG, München, D

SOBOTTKA, Helmut, Dipl.-Ing., Technischer Überwachungs-Verein Rheinland e.V., Köln, D

SPIESS, Stephan, Dipl.-Ing., International Harvester Company mbH., Neuss, D

SPIGT, Cornelis Ludovicus, Dr. Ir., N.V. Philips, Philips Research Laboratories, Eindhoven, NL

SPRENGEL, Uwe, Dr.-Ing., Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt e.V., Programmvorbereitung, Porz, D

STEIFER, George F., Chrysler Corporation, Chatham (Mich.), USA

SUGIURA, H., Honda Motor Comp. Ltd., Tokyo, J

SUHR, K.A., Dr., Direktor, Mobil Oil AG, Wedel, D

SUMIE, Arata, Engineer, Mitsubishi Motors Corp., Tokyo, J

SUTTROP, F., Dr.-Ing., Fachhochschule Aachen, Aachen, D

SWERTZ, Theo, Vorstandsmitglied, Gottfried Hagen AG, Köln, D

SZABO, Georg, Dipl.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D

SZYMANSKI, Wolfgang, Ing., Klöckner-Humboldt-Deutz AG, Köln, D

SCHAAF, Hanno, Dipl.-Ing., Maschinenfabrik-Augsburg-Nürnberg AG,
München, D

SCHACKE, Helmut, Dr., Institut für Physikalische Chemie, Universität
Göttingen, Göttingen, D

SCHÄFER, Hans-Jürgen, Dipl.-Ing., Volkswagenwerk AG, Wolfsburg, D

SCHAFFRATH, Manfred, Dr.-Ing., Lehrstuhl für Angewandte Thermodynamik,
Technische Hochschule Aachen, Aachen, D

SCHAUER, Wolfgang, Dipl.-Ing., Dornier System GmbH, Friedrichshafen, D

SCHIFERLI, Johannes Willem, Ir., Philips Natuurkundig Laboratorium,
Waalre, NL

SCHILLING, Alphonse, Coordinator Lubes & Chemicals, Texaco Services
(Europe) Ltd., Brüssel, B

SCHLIEP, Erich, Dr., Abteilungsdirektor, VEBA-Chemie AG, Gelsenkirchen-Buer, D

SCHLUNDT, Dieter, Dipl.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D

SCHMAUCH, Lothar, Ing. (grad.), Battelle-Institut e.V., Frankfurt, D

SCHMIDT, Gerd, Dipl.-Ing., Lehrstuhl für Angewandte Thermodynamik,
Technische Hochschule Aachen, Aachen, D

SCHMIDT, Friedrich, Dipl.-Ing., Stadtbaukommissär, Magistrat der Stadt
Wien, Wien, A

SCHMIDT, Reinhold, Dipl.-Ing., Siemens AG, Erlangen, D

SCHMIDT, Udo, Dr., Klöckner-Humboldt-Deutz AG, Köln, D

SCHMIDT, Volker, Ing. (grad.), Robert Bosch GmbH, Köln, D

SCHNEIDER, Arnulf, Dipl.-Ing., Dozent, Fachhochschule Konstanz,
Konstanz, D

SCHNEIDER, Dr., Brown, Boveri & Cie Aktiengesellschaft, Mannheim, D

SCHNELL, Erwin, Direktor, Klöckner-Humboldt-Deutz AG, Oberursel, D

SCHÖFFEL, Helmut, Ing. (grad.), Brown, Boveri & Cie Aktiengesellschaft, Mannheim, D

SCHÖNDORF, Prof. Dr.-Ing., Fachhochschule Köln, Fachbereich Fahrzeugtechnik, Köln, D

SCHOLZ, Lothar, Gruppenleiter, Daimler-Benz AG, Stuttgart, D

SCHOOFS, René, Ing., Brüssel, B

SCHRECK, Helmut, Dipl.-Ing., Institut für Kraftfahrwesen, Technische Hochschule Aachen, Aachen, D

SCHULTE, Hermann J., Redakteur, VDI-Verlag GmbH, Redaktion Umwelt, Düsseldorf, D

SCHULTEN, Christian, Ing., Heinrich Gillet KG, Edenkoben, D

SCHULTZ, O.W.O., Geschäftsführer, Fahrzeugstätten Falkenried GmbH, Hamburg, D

SCHULZ, R., Environmental Protection Agency, Ann Arbor (Mich.), USA

SCHWÄRZEL, Werner, Dipl.-Ing., Leiter der Motorenkonstruktion, Adam Opel AG, Rüsselsheim, D

SCHWARTZ, Hans-Jürgen, Dr., Abteilungsleiter, VARTA-Batterie AG, Kelkheim, D

SCHWARZBAUER, Gerd, Dr. Dipl.-Ing., Steyr-Daimler-Puch AG, Steyr, A

SCHWEIZER, Walter, Ing., Krafthandverlag, Bad Wörrishofen, D

STABLAD, John R., Dr. h.c., Swedish Board of Technical Development, S

STARKE, Klaus, Dipl.-Ing., BASF AG, Ludwigshafen, D

STEPUTAT, Helmut, Ing. (grad.), AK-Chemie GmbH & Co KG, Biebesheim, D

STERNLICHT, Beno, Dr., Technical Director and Board Chairman, Mechanical Technology Incorporated, Latham (New York), USA

STIEF-TAUCH, H.P., Europäische Gemeinschaften, Brüssel, B

STOJEK, Dieter, Dr.-Ing., Leiter der Motorenentwicklung und Konstruktion, Ford-Werke AG, Köln, D

STORK, Dieter, Dr.-Ing., Audi NSU Auto Union AG, Neckarsulm, D

STORK, Eric O., Deputy Assistant Administrator for Mobile Source, Air Pollution Control, Environmental Protection Agency, Washington D.C., USA

STREICHER, Kurt, Dipl.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D

STRELOW, Roger, Assistant Administrator for Air and Waste Management, Environmental Protection Agency, USA

STRUCHTRUP, Dieter, Ing. (grad.), International Harvester Company mbH, Neuss, D

TAKAHASHI, Keiji, Düsseldorf, D

TAKEI, Michio, Engineering Manager, Nissan Motor Co., Brüssel, B

TAUTENHAHN, Wolfram, Dipl.-Ing., Volkswagenwerk AG, Wolfsburg, D

TESAREK, Dipl.-Ing., Lehrstuhl für Verbrennungskraftmaschinen, Technische Hochschule Darmstadt, Darmstadt, D

THAIS, Ulrich, Student, Institut für Kraftfahrzeuge, Technische Universität Berlin, Berlin, D

THIELE, Hubertus, Dr.-Ing., Robert Bosch GmbH, Schwieberdingen, D

THOLEN, Paul, Dipl.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D

THOMAS, M., Fachhochschule Köln, Köln, D

THOMAS, Reiner, Dipl.-Ing., Gesellschaft für elektrischen Straßenverkehr mbH, Düsseldorf, D

THOMS, Ulrich, Dipl.-Ing., Institut für Verbrennungskraftmaschinen, Technische Universität Braunschweig, Braunschweig, D

THUR, George M., Chief, Power Systems Development Branch, Alternative Automotive Power Systems Division, Environmental Protection Agency, Ann Arbor (Mich.), USA

THURM, Uwe-Henning, Dipl.-Ing., Robert Bosch GmbH, Köln, D

TIEDEMA, Pier, Dipl.-Ing., Institut voor Wegtransportmiddelen TNO, Delft, NL

TISON, Ray, Engineering Assistant, Escher Technology Associates, St. Johns (Mich.), USA

TITZE, Gerd, Techniker, Deutsche Vergaser Gesellschaft mbH & Co KG, Neuss, D

TJOA, T. Bing, Dipl.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D

TOZIANE, T., Mitsubishi Motors Corp., Minato-Ku, Tokyo, J

TOPPER, Leonhard, Energy Policy Analyst, Office of Energy R & D Policy, National Science Foundation, Washington D.C., USA

TORAZZA, Giovanni, Engineer, FIAT, Torino, I

TORRES, Fernando, Dipl.-Ing., Institut für Kraftfahrwesen, Technische Hochschule Aachen, Aachen, D

TRÖSTER, Kurt, Dipl.-Ing., Verein Deutscher Ingenieure, Kommission Reinhaltung der Luft, Düsseldorf, D

TSCHÖKE, Helmut, Dipl.-Ing., Universität Stuttgart, Stuttgart, D

TYRRELL, Edward, Commander (Rn retired), Department of Industry, London, GB

UNDERWOOD, Arthur F., Consultant, Rochester (Mich.), USA

UPWARD, Roger Alan, Principal Engineer, Ford Motor Company, Laindon, GB

URLAUB, Alfred, Dr.-Ing., Maschinenfabrik-Augsburg-Nürnberg AG, München, D

VANDONKELAAR, Peter, Ing., Outboard Marine Belgium S.A., Brügge, B

VEENEMANS, C., Van Doorne's Personenautofabriek DAF B.V., Geldrop, NL

VEIGEL, W. Martin, Direktor, Deutsche Vergaser GmbH & Co KG, Neuss, D

VERDIANI, Daniel, Dr.-Ing., Chef de la Délégation de la Commission des Communautés Européennes, Bruxelles, B

VERNON, Jack H., President, Scientific Energy Systems Corp., Watertown (Mass.), USA

VERSMOREN, H.Th.P., Assistent-Moteur, N.V. Philips Gloeilampenfabrieken, Eindhoven, NL

VISSER, Erich, Ing. (grad.), Klöckner-Humboldt-Deutz AG, Köln, D

VLIET, van, A.C.M., Yamaha Motor N.V., Amstelveen, NL

VOGEL, Wolfgang, Webasto-Werk W. Baier KG, München, D

VOGES, Christoph, Dipl.-Ing., Deutsche Vergaser GmbH & Co KG, Neuss, D

VOGT, Wilhelm, Dr., Farbwerke Hoechst AG, Frankfurt, D

VOGTHERR, Dieter, Regierungsbaurat, Kraftfahrt-Bundesamt, Flensburg, D

VOIGT, Dieter, Dipl.-Ing., Institut für Kraftfahrwesen, Technische Hochschule Aachen, Aachen, D

VONDRAN, Willy, Obering., Mahle GmbH, Stuttgart, D

WACKER, Erich, Dipl.-Ing., Karl Schmidt GmbH, Neckarsulm, D

WACHTER, J., Prof. Dr.-Ing., Lehrstuhl und Institut für Thermische Strömungsmaschinen der Universität Stuttgart, Stuttgart, D

WAGNER, Charles Edward, Senior Research Staff Engineer, Chrysler Corporation, Detroit (Mich.), USA

WAGNER, Eberhard, Dipl.-Ing., Institut für Physikalische Elektronik der Universität Stuttgart, Stuttgart, D

WAGNER, Rudolf, Dr.-Ing., Siemens AG, Erlangen, D

WAGNER, Wolf-Dietrich, Dipl.-Ing., Daimler-Benz AG, Stuttgart, D

WAHNSCHAFFE, Jürgen, Dipl.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D

WALDE, Nils, Civilingenjör, Saab-Scania AB, Soedertaelje, S

WALDEYER, Heinrich, Dr.-Ing., Technischer Überwachungs-Verein Rheinland e.V., Köln, D

WALWIJK, van, Eduard, Ir., DAF Truck B.V., Eindhoven, NL

WALZER, Peter, Dr., Volkswagenwerk AG, Wolfsburg, D

WANDERS, Kurt, Dipl.-Phys., Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt e.V., Porz-Wahn, D

WARMUTH, Heinrich, Dipl.-Ing., Deutsche Verkehrswissenschaftliche Gesellschaft e.V., Köln, D

WASSNER, Lothar, Dr. rer.nat., Volkswagenwerk AG, Wolfsburg, D

WEBER, Helmut, Dipl.-Ing., Obering., Rheinisch-Westfälischer Technischer Überwachungs-Verein e.V., Essen, D

WEIDEMANN, Dipl.-Ing., Institut für Verbrennungskraftmaschinen, Technische Hochschule Darmstadt, Darmstadt, D

WELSCHOF, Gerhard, Dr.-Ing., International Harvester Comp. mbH, Neuss, D

WELTENS, Herman, Lehrstuhl für Angewandte Thermodynamik, Technische Hochschule Aachen, Aachen, D

WEST, Hans, Dipl.-Ing., Verein Deutscher Ingenieure, Düsseldorf, D

WEST, James T., Manager, Ford Motor Company, Dearborn (Mich.), USA

WEVER, B., Van Doorne's Personenautofabriek DAF B.V., Geldrop, NL

WEYRAUTHER, Gerd, Dipl.-Ing., Technischer Überwachungs-Verein Rheinland e.V., Köln, D

WIDDEL, Gerhard, Dipl.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D

WIEDE, Norbert, Ing. (grad.), Henkel & Cie, Düsseldorf, D

WIEDEMANN, Bernd, Dipl.-Ing., Volkswagenwerk AG, Wolfsburg, D

WIEDEMANN, F., Adam Opel AG, Rüsselsheim, D

WIEGAND, Herbert, Dipl.-Ing., Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt e.V., Institut für Angewandte Gasdynamik, Porz-Wahn, D

WIEGNER, Dr.-Ing., Technischer Überwachungs-Verein Rheinland e.V., Köln, D

WIESNER, Rudi, Dipl.-Ing., Ford-Werke AG, Köln, D

WIKSTRÖM, Hans, Project Engineer, Saab-Scania AB, Stockholm, S

WILDNER, Othmer, Dipl.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D

WILL, Karl-Heinz, Nissan Motor Deutschland GmbH, Düsseldorf, D

WILLMANN, Karl, Dr., Daimler-Benz AG, Stuttgart, D

WILLMERDING, Günter, Dipl.-Ing., Battelle-Institut e.V., Frankfurt, D

WILLUMEIT, Hans-Peter, Prof. Dr.-Ing., Institut für Landverkehrsmittel, Technische Universität Berlin, Berlin, D

WILSON, John L., Dr., National Engineering Laboratory, Glasgow, GB

WINKLER, Eberhard, Dr., Bayerisches Landesamt für Umweltschutz, München, D

WIRT, Gerd, Dipl.-Ing., Bayerische Motoren Werke AG, München, D

WISDOM, James, Lucas Electrical Co. Ltd. Birmingham, GB

WITBACH, Heinz F., Ing. (grad.), Klöckner-Humboldt-Deutz AG, Köln, D

WITTIG, Ejnar, Dipl.-Ing., Daimler-Benz AG, Stuttgart, D

WITTIG, Sigmar L.K., Prof., Purdue University, Department of Mechanical Engineering, Lafayette, USA

WÖBKY, Peter, Ing., Deutsche Vergaser GmbH & Co KG, Neuss, D

WÖRNER, Siegfried, Ing. (grad.), J. Eberspächer, Esslingen, D

WOISETSCHLÜGER, Ernst, Krafthandverlag, Schwäbisch Gmünd, D

WOLF, Willy, Obering., Dr., BASF AG, Ludwigshafen, D

WOLFF, Hans-Christian, Dipl.-Ing., Deutsche BP AG, Hamburg, D

WOLSING, Wilhelm, Dipl.-Ing., Engelhard Kali-Chemie, AutoCat GmbH, Hannover, D

WOSCHNI, Gerhard, Prof. Dr.-Ing., Institut für Verbrennungskraftmaschinen, Technische Universität Braunschweig, Braunschweig, D

WURM, Joseph-Gerald, Dr. Sc., Administrateur principal, Commission des Communautés Européennes, Brüssel, B

WYK, van, Willem F., Ing., DAF B.V., Geldrop, NL

YAMADA, Toyotara, General Manager, Toyota Motor Co. Ltd., Brüssel, B

ZACHARIAS, Friedemann, Dr.-Ing., Motoren-Werke Mannheim AG, Augsburg, D

ZAHR, Karl-Heinz, Dipl.-Ing., Deutsche Vergaser Gesellschaft mbH & Co KG, Neuss, D

ZAJONTZ, Joachim, Dr.-Ing., Akademischer Direktor, Technische Universität Claustal, Claustal-Zellerfeld, D

ZANDER, Walter, Dr. Dipl.-Ing., Audi NSU Auto Union AG, Ingolstadt, D

ZAPF, Horst, Dr.-Ing., Maschinenfabrik-Augsburg-Nürnberg AG, München, D

ZELINKA, Robert, Dipl.-Ing., Maschinenfabrik-Augsburg-Nürnberg AG, München, D

ZESCHMANN, Ernst-G., Dipl.-Ing., Deutsche Shell AG, Hamburg, D

ZIMMERMANN, Horst, Dipl.-Ing., Klöckner-Humboldt-Deutz AG, Köln, D